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Journal of the
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TEAMWORK IN THE SOLUTION OF WATER PROBLEMS[1]

Harvey O. Banks,[2] M. ASCE
(Proc. Paper 1497)

There are four aspects of teamwork in the solution of water problems: (1) teamwork in the uses of water; (2) teamwork among the many agencies who plan, construct and operate water development projects; (3) teamwork among the professional and scientific fields in adding to the store of knowledge concerning the nature, occurrence, control and utilization of water; and finally, (4) teamwork between the professional and technical people who deal with water on the one hand and the general public on the other hand, in solving these problems.

Today, competition for water is becoming more and more intense, not only between areas and the various uses of water, but also in the use of the few remaining good reservoir sites. Irrigation must continue to have a high priority in future developments but other uses of water must be given full consideration.

It has become apparent, in California and in most other areas as well, that in planning and operating water control and conservation projects consideration must be given to all facets of the problem in relation to all resources, natural and human. Some few projects are planned solely for municipal use, and others primarily for irrigation or industrial supplies. Still others are being planned for recreational use, or for the benefit of fishlife. However, most projects of the future will each serve a variety of purposes.

There is no other natural resource, unless it is air, which has such an impact on civilization as does water. This has been true ever since the first water was crudely diverted from the Tigris and Euphrates Rivers during the dawn of civilization in Asia Minor. It is more true today as populations near the "exploding" point, and civilizations have evolved which are totally dependent on vast amounts of water.

Although there still is about the same amount of water falling on the earth in the form of precipitation as there was 25 or 50 years ago, the resource is

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1. Paper presented to Intersociety Conference on Irrigation and Drainage, San Francisco, Calif., April 29, 1957.
2. California Director of Water Resources.

limited from several standpoints. There are more people and more uses of water than there were in the past. Civilization's alterations on the face of the earth probably have made somewhat less water available in the form of runoff and have decreased opportunities for natural percolation into the ground water basins. Future conservation of large amounts of water is limited because of the scarcity of additional good reservoir sites, and lack of sufficient ground water storage capacity.

The time is past when water problems can be solved on the basis of individual problems, or project by project. There was a time when planning on a watershed scale was considered the ultimate in broad gauge outlook. Already in California and elsewhere there are in actual operation large scale inter-regional transfers of water, from one watershed to another and from one basin to another, often at great distances apart. There are on the drawing boards many more such developments.

The time also is past when most single or even dual purpose water developments can properly be considered by any large public entity such as a state or federal governmental agency. Projects with limited objectives create as many problems as they solve. Such projects on a limited scale, for local purposes only, could be an exception, but there is little excuse for a large scale development with limited objectives.

Water developments from this date on must consider the balanced use of water in all of its aspects. Limited concepts of water development such as solely for irrigation, for municipal, or for power purposes alone must be set aside in favor of the broadest possible concepts which take into consideration the impact on all of society. Among the many uses of water that must be considered in arriving at the proper balance are municipal, irrigation and industrial water supplies, hydroelectric power generation, fish and wildlife, recreation, navigation, salinity control, and finally, disposal of sewage and industrial wastes. At the same time, quality control and drainage must be accorded due consideration. Ground water cannot be treated as a thing apart; rather surface and ground waters must be considered together. Waste disposal cannot be ignored since ultimately much of the liquid fraction of waste projects resulting from human activity must be disposed of to water courses and ground waters. Preservation and enhancement of fish and wildlife resources is rapidly assuming paramount importance as population growth encroaches on wild areas and as popular demand mounts for more hunting and fishing opportunities. Likewise, the provision of adequate recreational facilities along flowing streams and in connection with the water areas of reservoirs becomes of great significance to the well-being of all people.

Each new development must be made to yield its maximum, not only in economic benefits but in the more intangible benefits, some of which are not yet fully appreciated by water resource engineers, economists and others concerned with water problems.

Many of the different uses of water are mutually conflicting. Operation of a reservoir for irrigation alone precludes much of a power operation, and offers little flood control. Operation for dilution and disposal of waste products is in conflict with other uses. The same is true of flood control operation, which produces little conservation. And so it goes, in every type of single-purpose operation.

Efforts of the planning, constructing, and operating agencies must be coordinated in teamwork to minimize these conflicts. Conflicts between the various uses of water must be resolved to bring maximum returns to all uses.

California has an excellent example of planning which includes many of the points mentioned. It is not a perfect example, but it is a start in the direction of multiple-use planning which views the problem from all aspects.

This is The California Water Plan, which is being presented to the State Legislature next month as a broad guide or master plan to which all future water development projects should reasonably conform. For purposes of illustration, this is, briefly, its background and its objectives.

The urgency of California's water problems can be illustrated by citing an example of the recent rapid growth of the State. In 1940, just before the beginning of World War II, California had a population of about 6,900,000. By 1950, this population had increased to about 10,600,000 and it is now estimated to exceed 14,000,000. The forecast ultimate population for the State is forty million. In 1950, the estimated seasonal shortage of developed water in the State was about 2,700,000 acre-feet, largely representing an overdraft on ground water storage. By 1955, water requirements had increased an additional 3,000,000 acre-feet per season. Allowing for the yield from new construction during the intervening period and for increasing the delivery of constructed works to their full potential wherever possible, the deficit aggregated nearly 5,000,000 acre-feet per year in 1955. Based upon reasonable forecasts of growth of the State during the next 10 years, it is indicated that the net shortage of developed water supply could amount to more than 10,000,000 acre-feet per season by 1965, if additional water conservation works are not constructed.

The need for the solution of the present and future water problems of California is clear. It is also clear from study of the past history of water development that future growth of the State will depend upon a coordinated statewide program for water development. The authorized Feather River Project, the first truly statewide project, will be the first major step in this direction. Construction will start in May, 1957. However, even if the project were constructed and in operation today and serving all areas of water deficiency, it would barely overcome the deficiencies of the present. In other words, the large water supply to be gained from the Feather River Project is fully needed today. Furthermore, unless we assume stagnation of the population at present levels, one or more additional projects of comparable size should be rapidly planned for construction in the near future. This fact should be cause for concern, for there is no reason to believe that California's phenomenal recent rate of growth will slow down now or in the near future. The need for immediate initiation of a statewide water development construction program is particularly acute because of the often-demonstrated time lag between the planning stage and the financing and construction stage of any large-scale project.

Recognizing these problems, the State Legislature in 1947 authorized comprehensive statewide investigations and studies, culminating, after 10 years of intensive effort and an expenditure of over eight million dollars, in "The California Water Plan," a master plan to guide and coordinate the planning, construction and operation of works by all agencies required for the control, conservation, protection, distribution and utilization of all of California's water resources, both surface and underground, for the benefit of all uses and all areas in the State.

What does "The California Water Plan" purport to do?

1. It evaluates the water supply available to California and describes the places and characteristics of its occurrence.

2. It estimates the water requirements, both present and future, for all purposes for each area of the State as best as can be foreseen now.

3. It points out (a) the watersheds where present estimates indicate surplus waters exist over and above the future needs for local development, and gives an estimate of such surplus, and (b) the areas of deficiency and the estimated deficiency for each such area, both at present and under conditions of ultimate development.

4. It outlines existing and prospective water problems in each area of the State.

5. It describes the uses to which the remaining unappropriated waters of the State should be put for maximum benefit to the people of all areas of the State.

6. It suggests the manner in which the waters of the State should be distributed for the benefit and use of all areas.

7. It proposes objectives toward which future development of the water resources of the State should be directed in all areas of the State, and suggests broad patterns for guidance toward these objectives.

8. It defines these objectives in terms of potential physical accomplishments which may be used to measure the merits of projects proposed for construction by any agency.

9. Finally, it demonstrates that the waters available to the State of California, including the State's rights in and to the waters of the Colorado River, are not only adequate for full future development of the land and other resources of the State, but also that physical accomplishment of these objectives is possible.

The California Water Plan shows how teamwork can be accomplished among those having interests in the various uses of water. It shows the way for truly multipurpose development by recommending full use of the remaining good reservoir sites, and is based on balanced use of water as among municipal, irrigation, and industrial water supplies, salinity control, quality control, fish and wildlife, and recreational uses, power generation, navigation and waste disposal. It includes provision for adequate flood control and drainage. It envisions conjunctive operation of surface and ground water storage reservoirs.

The California Water Plan takes cognizance of the competition between uses, and for reservoir sites, and indicates that the task of developing California's future water supplies must be a team job. It must be accomplished under the leadership of the State, but with the cooperation of federal, local and private entities, all operating within the framework which will provide the maximum benefits for all areas and all uses.

The second aspect of teamwork is that among agencies operating in the field of water development. There are good examples of federal-state cooperation or teamwork in developments proposed for the immediate future in California. The proposed federal contribution for flood control benefits accruing from Oroville Reservoir of the Feather River Project is one. This is a concept of long-standing and needs no elaboration here.

Another example of more than passing interest is the proposal for joint state-federal financing, federal construction and state operation of certain

features of the San Luis Unit of the Central Valley Project. San Luis Reservoir and certain associated facilities on the west side of the San Joaquin Valley is vital to both the federal San Luis Unit, and to the State's Feather River Project Aqueduct. There are measures before Congress, and before the California Legislature which would provide for joint financing, construction, and operation of San Luis which would permit all of its objectives to be carried out for both projects. This is a partnership proposal without known precedent in such a major undertaking, and is an excellent example of the type of teamwork mentioned.

At the same time, the current proposals in the California Legislature to advance to the Bureau of Reclamation funds for engineering work in advance of federal appropriations, to enable the Bureau to rush the job to completion a year earlier constitute a fine example of possible state-federal cooperation. Others include California's policy of cooperating with the federal government on certain flood control projects.

Another proposal by the State of California in the field of teamwork is that of state-local relationships in the matter of local water development projects. It has been proposed that the State participate financially in local projects to the extent of any statewide interest in that project. It is further proposed that a water development fund for many types of projects be set up, and that provision be made for long term loans or grants to local agencies which are willing to launch their own developments but which do not at present have the financial resources to do so.

Such loans and grants would be made when there is a statewide interest involved in the local project. Such interest would include balanced use of water resources, resolution of conflicts between competing groups, making full and best use of available dam and reservoir sites, an equitable distribution of benefits and costs between uses and areas, and direct project effects which extend beyond the boundaries or jurisdiction of a particular public agency.

In a word, The California Water Plan is based on coordination and teamwork at all levels, and on all possible aspects of water control and use in relation to the State as a whole.

In connection with these broad concepts in planning, construction and operation of water developments, there is a pressing need for more and broader scientific knowledge concerning water development and related subjects. This is the third aspect of teamwork to be discussed. For example, there is a vital need for more information on consumptive uses of water, the biggest single item in the disposal of water as it falls on the land as precipitation. Experimental data in this field are quite limited. There is an urgent need for long time studies giving consideration to the many variables such as vegetative types, elevation, climatic factors, soils, irrigation practices, and others.

All of these factors are involved in the teamwork required in the control and use of water by engineering methods—methods that catch, hold, and move water in and from our streams. Concern, however, in the development of The California Water Plan has not been limited to consideration of reservoirs, distribution systems and ground water basins. It has of necessity gond beyond these downstream locations up to the watersheds themselves where many things can happen and can be done to affect waters' flow and quality. Control over water in watershed lands can do much to facilitate the handling of water after it has left these lands.

It will take, however, the highest type of teamwork to accomplish this, for the problem is even more complex here than in the downstream areas. The job of providing effective water control would be difficult and complicated enough if water were the only crop for which watershed lands were managed, but in most circumstances this is not the case, for these lands also produce timber and forage, minerals and oil, some agricultural crops and the lands themselves are used for recreation, hunting, and fishing. Some conditions necessary for producing and harvesting and renewable crops, and some conditions required for or produced by the other uses of the land, are not all in harmony with upstream control of water quantity and quality. The need to provide for these crops and uses makes watershed management even more complex in many places.

Much has been done in California and throughout the Nation on these phases of water control—forest fire prevention and suppression systems have been intensified, logging practices have been improved, range management programs introduced, agricultural practices perfected, forage grasses substituted for brush and denuded areas reforested, but this work has never been clearly evaluated in terms of its effect on water production and control.

Many of the critical questions yet unanswered in the full solution to California's water problems relate directly to the watershed management phase of water control. Principles and techniques relating to watershed management are still in their early stages of development. One of the next important steps forward in the development of our water resources is to place watershed management investigation and research on a sound continuing and comprehensive basis.

More must be known about the effect of control of fire, logging, grazing, and other land management practices on the quality, quantity, and timing of water yields. Serious attention must be given to areas where watershed conditions have deteriorated because of past use or misuses and where something can be done to correct the conditions. The most urgent need is to evaluate past practices and experiences so that the application of recommended practices to particular conditions can be made clear, and means to insure their adoption be developed. The teamwork required among private landowners, governmental agencies, and the host of professional people dealing with these problems presents a tremendous challenge. This watershed management phase of water development is an example of the kind of information which must be developed and put to use.

A fine example of this teamwork is the recent research program initiated by the California Forest and Range Experiment Station and the California Department of Water Resources on the management of the snowpack in the high mountains of California to learn how to slow snow melt and reduce evaporation to control and increase the volume of runoff.

There is a similar serious need for further information and exchange of such data in other related fields.

How much is known, for example, concerning the useful life of a reservoir, and the factors affecting it? Some data is available on this important facet of water supply development, but not enough.

Ground water is one of the most important factors in any overall water development program, yet the surface has barely been scratched in a search for knowledge on this subject. Relatively little is known of the geology of many important ground water basins and of the characteristics such as

specific yield, of various water bearing materials, yet complete information is absolutely vital to full development of water resources for all uses.

Some progress has been made in the matter of water quality, but here again the field for investigation is wide open. Relation of water quality to soils and crop yields, selection of proper cropping patterns, weeds, plant diseases and insects in relation to water use—all are factors which have effects on water requirements.

Drainage, proper land use, health problems, the Nation's changing food habits, costs, the national economy—all of these are things which should be taken into consideration in the type of planning which is now necessary.

In all of these, members of the various scientific fields—the engineer, the forest management expert, the soils technician, the agriculturist, the economist, the financier, the health technician—all must achieve a greater measure of teamwork and coordination if this concept of multiple use for all facets of society is to work.

Finally, one of the most important factors in the entire picture is the body politic, the people who are most concerned with what the professional people do in this all-important field, and who, in the end, make the decision as to what is to be or is not to be done.

There must be a greater exchange of technical information among the various agencies and the various scientific disciplines which make up the field.

What about the flow of non-technical information to the people who are directly concerned, and who are paying the bill? This is an aspect of teamwork which technical men all too often are inclined to dismiss as being non-professional and out of their field.

Too often, progress in the water development field is stymied because of inadequate communication of such information to the general public, and in a manner which can be understood by lay people.

It is not difficult for the people of a given political entity, state or local, to vote project funds after the reservoir or well has gone dry. That is something they can understand, but of course action at that stage of the game is far too late.

The responsibility of the professional men charged with leadership in this field to the public cannot be overestimated. Responsibility to the public means not only taking leadership in programs believed to be right, but also placing the facts, in understandable form, before the public.

The history of this nation has proved conclusively that an informed and enlightened public, when free to make a choice, will make decisions leading to the greatest benefit for the greatest number.

That is the final link in this chain of teamwork which is vital to continued sound water development. Achieving such teamwork is a large order, and may require many changes in thinking and much soul-searching.

There is, however, no other choice, Water is vital to civilization. It is becoming a scarce article. Opportunities for further development are more and more limited. Either we advance as a team, or fall, area by area.

In paraphrasing the theme of this conference, it seems that rather than "Can Man Develop a Permanent Irrigated Agriculture?", it might be "Can Man Develop a Water Development Program in Relation to the Entire Societal Structure?"

With the kind of teamwork described, the answer is yes.

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ENGINEERING IN THE SOIL CONSERVATION SERVICE [a]

C. J. Francis[1]
(Proc. Paper 1498)

SUMMARY

This paper outlines the engineering activities of the Soil Conservation Service, a federal agency engaged in giving technical and sometimes financial assistance to groups and individual farmers and ranchers in developing sound soil and water conservation programs. It places particular emphasis on the engineering aspects of the new Watershed Protection and Flood Prevention Program, Public Law 566, which is administered by the Soil Conservation Service.

When the national soil conservation program was inaugurated about 25 years ago, emphasis was placed on solving the problems of wind and water erosion. After a few years of experience it was found that erosion control practices alone were too limited to provide a sound conservation program on a national basis. Thus, the scope and extent of the program has gradually been broadened to cover all aspects of soil and water conservation as it applies to agriculture and related interests.

Soil conservation has come to mean proper land use, protecting land against all forms of soil deterioration, rebuilding eroded and depleted soil, improving grasslands, woodlands, and wildlife lands, conserving water for farm and ranch use, proper control and use of water to provide for drainage, irrigation and flood prevention, building up soil fertility and increasing yields, and farm and ranch income.

The responsibility for furnishing technical assistance to individuals and groups to attain these objectives on the private lands of the nation is vested

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a. Paper presented at meeting of American Society of Civil Engineers, Jackson, Miss., February 19-21, 1957.

1. Director, Eng. Div., Soil Conservation Service, Washington 25, D. C.

in the Soil Conservation Service. As an action agency of the Department of Agriculture, it provides technical and in some situations financial assistance to farmers, ranchers and others through soil conservation districts. These districts are legal subdivisions of the state—democratic organizations managed by elective officers for the express purpose of conserving our soil and water resources.

The SCS has as its primary objectives (1) the development of a basic conservation plan for every farm and ranch in the nation that has conservation problems, and (2) the protection and improvement of watersheds as a means of reducing flood and sediment damage and safeguarding water supplies for both rural and urban use. The program is wholly voluntary, thus, the responsibility for achieving the objectives of soil and water conservation rests with the farmers and ranchers. The use and control of water is basic to the development of a sound conservation program. Land and water are inseparable. Water initially is an agricultural resource. The water supply occurring in major streams, lakes, and underground reservoirs originates on the farms and ranches of the nation. These small watersheds collectively provide the nation with its water supply. The management of the land on which water fall is an important key to its control and utilization.

Whenever water is controlled for use or disposal, engineering sciences play an important role. This fact was recognized at the time the Soil Conservation Service was organized and as the program expanded, engineering services have become more and more important. However, engineering is only one of the sciences employed in developing a balanced conservation program. Many other sciences such as soils, agronomy, range, biology, and forestry are essential to the development of such a program. The integrated effort of all technical fields is required to develop and carry out the conservation program. As watershed work embodies all elements of conservation engineering a brief discussion of SCS activities in that field will emphasize the categories of engineering work with which SCS is concerned.

Flood Prevention Program

SCS operations in watershed work started with the passage of the Flood Control Act of 1936. This Act among other things provided that ". . . . . federal investigations of watersheds and measures for runoff and water flow retardation and soil erosion prevention on watersheds shall be under the jurisdiction and shall be prosecuted by the Department of Agriculture. . . . . "

Survey reports were submitted to Congress under the authority of this Act and in 1944, eleven watersheds were authorized for operations. The watersheds are Buffalo Creek in New York; Potomac River in parts of Virginia, West Virginia, and Pennsylvania; Coosa River in Georgia; Little Tallahatchie and Yazoo Rivers in Mississippi; Trinity and Colorado Rivers in Texas; Washita River in Oklahoma; Little Sioux River in Iowa; and Santa Ynez and Los Angeles Rivers in California. The total drainage areas of these eleven watersheds is approximately 30 million acres.

The Potomac, Coosa, Trinity, Colorado, and Washita River projects are being developed to protect agricultural land from flooding and siltation. The structural measures employed consist almost exclusively of retarding dams and associated channel improvement. It is estimated that approximately 2,160 retarding dams will be constructed to provide for flood prevention in

these five projects. As of June 30, 1956, 293 retarding structures have been built or are under construction. In the Washita project which is typical, the drainage area above the structures will amount to approximately 40 percent of the entire watershed. The flood plain areas inundated by the permanent pools of the floodwater retarding structures is approximately 5 percent of the total. Only about one third of the flood plain lands included in the reservoir areas is presently under cultivation.

The Los Angeles project involves channel improvement works on tributaries of the Los Angeles River designed to provide flood protection to adjoining land and stabilization of channels to reduce erosion and downstream siltation. Channel alignment is improved and capacity provided to discharge the design storm. The protective works vary from complete channel lining with reinforced concrete and reinforced asphaltic concrete in some places to single and double row-fence bank revetment in combination with wire and concrete stabilizing sills. The type of channel protection used is dependent on the value of the property to be protected and the physical conditions of the channel. This work is done in cooperation with the Los Angeles County Flood Control District. The Department of Agriculture's participation in this program is expected to be completed within a relatively few years.

The structural work on the Santa Ynez and Little Sioux projects is designed primarily to provide for grade stabilization and sediment control. Reinforced concrete drop spillways and earth-fill drop inlet structures are used. While a lot of work remains to be done, the Santa Ynez project is presently inactive because of the inability of the local interests to obtain the required easements. The Little Sioux project is moving ahead on schedule.

The Buffalo River project involves bank and channel stabilization measures designed to reduce sedimentation in the Buffalo Harbor. Rock riprap is used to provide for stabilization.

The Tallahatchie and Yazoo Rivers project is a segment of the Yazoo River watershed. Sheet and gully erosion with resultant siltation of downstream channels are the dominant problems. Land use adjustment is the key phase of the over-all problem. In addition to the all important revegetative measures, some flood retarding reservoirs are proposed.

Pilot Watershed Program

As a result of the work done under the flood prevention program, the occurrence of floods causing heavy agricultural damage, and the increasing public interest in the watershed treatment, the 83rd Congress made an initial appropriation of $5,000,000 to start operations on approximately 65 pilot watersheds. The pilot watershed projects were established to determine the best approach to the development of a national integrated program of flood prevention and watershed protection.

The total project cost is now estimated to be about $70,000,000. This is to be borne equally by the federal government and the sponsoring agencies or groups. The federal government's contribution is spent for structural measures designed to provide for flood prevention and sediment control and reduction. The sponsoring agencies give assurance that a complete land use and treatment program is applied to the contributing drainage area, and provide material, labor, rights of way, and cash which, in the aggregate, match the funds appropriated by the federal government.

The authorized projects are located in 34 states. They range in size from approximately 2,500 acres to more than 200,000 acres and the aggregate of all drainage areas is about 3 million acres. Actual construction operations started on the authorized projects in September 1954. Most of the projects will be completed in 1958. A total of approximately 242 retarding dams have been completed or were under construction as of June 30, 1956. Based on the plans that have been prepared, approximately 750 floodwater- retarding structures and 1,900 grade stabilization and sediment control structures will be required to bring the projects to completion.

Watershed Protection and Flood Prevention

As a follow-up on the Pilot Watershed legislation, the second session of the 83rd Congress recognized the need for permanent legislation to govern watershed activities and as a result enacted the Watershed Protection and Flood Prevention Act, Public Law 566 in 1954. This Act authorizes the Secretary of Agriculture to cooperate with local organizations, including states, in planning and carrying out works of improvement as a means of watershed protection. It provides the permanent legislation needed to continue the watershed approach to insure watershed protection and flood prevention on agricultural lands in the tributary and smaller streams. It is expected that all watershed activities for which SCS has responsibility will gradually be modified to the extent permitted by law to allow operations to be carried out under a single unified policy.

This watershed legislation, some people have said, will conflict with the program authorized under other legislation in the development of flood control works on the larger streams. In order that the Department's position on this matter may be expressed, the following is quoted from Mr. D. A. Williams' speech to the River and Harbor Conference in Washington, D. C., May 25, 1954. "I would like to say emphatically—and here I only reiterate what my distinguished predecessors Dr. Hugh H. Bennett and Dr. Robert M. Salter have said—that upstream watershed protection programs are complementary to and not a substitute for needed downstream improvements. At the same time it is equally obvious that downstream river improvements cannot be a substitute for upstream watershed protection. Such work can, of course, produce no direct physical benefits to small valleys and upstream watershed lands above the works. Nor on the other hand can the combination of land treatment and inter-related small dams and channel improvements up in the watershed provide adequate control of disaster-type floods that afflict such cities as Pittsburgh, Cincinnati, Omaha, or Kansas City.

"Upstream programs developed by local groups with assistance from the Department of Agriculture are multiple purpose in nature—aimed at soil conservation, water conservation, including drouth relief, local drainage, local irrigation (as distinguished from reclamation) <u>and</u> flood protection. Upstream flood protection as we conceive it, cannot generally prevent disasters in the major stream valleys caused by runoff from the great storms such as that which occurred over the Kansas River valley in 1951. Upstream watershed protection <u>can</u>, however, prevent the frequent overflows of the small valleys that cause most of the headwater flood damages—providing land treatment and inter-related small structures are planned and installed concurrently or in proper sequence."

These projects are not federal projects. The local people originate the projects, develop the over-all plan, carry out construction, and assume responsibility for operation and maintenance. The SCS gives technical and financial assistance only on request when the requirements of the Act are met.

Public Law 566, Watershed Protection and Flood Prevention Act, was approved in August 1954, and amended by Public Law 1018 in August 1956. The Act as amended authorizes technical and financial aid to local organizations in planning and carrying out works of improvement for (1) flood prevention, (2) agricultural water management, including irrigation and drainage, and (3) non-agricultural water management, including municipal or industrial water supply, recreation, pollution abatement by stream flow regulation, etc. A good start has been made in getting the program underway. A total of 599 applications for watershed projects have been made in 46 states. Of the applications, 257 in 45 states have been approved by the responsible state officials and by the SCS for making investigations and surveys needed to develop watershed work plans. As of this date 40 projects in 24 states have been approved for construction. Actual construction operations have been started on two projects.

The basic measures employed by the Soil Conservation Service to provide for flood prevention may be divided into two broad categories (1) land use and treatment measures and (2) structural measures designed to reduce floodwater and sediment damage to supplement or augment the land treatment measures.

Land treatment measures are the basic measures employed by SCS in its operation program to provide for soil erosion control and moisture conservation. A sound land treatment program is a prerequisite to the installation of structural measures. Examples of these measures are rotations, contouring, strip cropping, stubble mulching, terracing, grassed waterways, gully control and stockwater developments. There are many others. They are usually applied on an individual farm basis as part of a conservation farm plan and their major benefits accrue to the individual farm.

It is recognized that land treatment alone will not give adequate protection against flood damage during periods of exceptionally heavy or prolonged rainfall. The water storage and infiltration capacities resulting from such measures are limited. In most instances structural measures need to be combined with land treatment measures to provide for adequate floodwater and sediment control.

The major structural measures used in the watershed program consist of retarding dams, grade stabilization structures, sediment detention structures, and stream channel improvement works. Only those structural measures having a direct measurable effect in reducing erosion, floodwater, and sediment damage affecting groups of landowners, communities, and the general public are eligible for financial assistance under the program. Such measures ordinarily require group action for their installation and always require group benefits for their justification.

Scope of Act

A few salient points regarding the scope of the Act may be of interest. Individual project watershed areas cannot exceed 250,000 acres. The total capacity of any structure is limited to 25,000 acre feet.

The total capacity allowable to floodwater detention in any single structure is limited to 5,000 acre feet.

Agricultural water development and management, for example irrigation and drainage is an authorized class of work.

Federal financing provides for 100 percent of the flood prevention feature of a project, except that local interests must provide easements, rights of way, water rights, and operation and maintenance.

For irrigation and drainage and other agricultural water management work, the local organizations pay that share of the cost considered equitable and as deemed necessary by the Secretary of Agriculture on the basis of direct identifiable benefits.

Local watershed organizations may employ professional engineers acceptable to the Secretary of Agriculture on flood prevention or agricultural water management measures. The local interests are reimbursed for the cost of such services for flood prevention and for agricultural water management when justified by benefits accruing to other than direct identifiable beneficiaries.

For the municipal or industrial water supply features of a project the local organization must provide and pay for engineering services and pay the entire cost of construction, as well as provide land easements and rights of way.

The construction, operation, and maintenance of the works of improvement is the responsibility of the sponsoring organization.

River Basin Planning

The development of major river basins involves coordination of agricultural interests with those of industry and municipalities. Public Law 566 gives recognition to this need. The SCS is authorized to participate in basin and project-type developments in helping to determine the agricultural suitability of the land, make recommendations regarding the best agricultural use and prepare cost estimates of the agricultural phases. The SCS is presently joining with the Bureau of Reclamation, the Corps of Engineers, and other federal agencies in coordination studies on several basin programs. Engineering activities in these cooperative studies primarily are concerned with the structural phases of upstream watershed protection, and the planning and estimating cost of farm drainage and irrigation systems adapted to the soil and other physical features.

Snow Surveys

Availability of water is an important factor in planning irrigation systems.

The Department of Agriculture pioneered stream flow forecasting from snow surveys which are now conducted by SCS in cooperation with other agencies, states, irrigation districts, and industry.

In those areas where irrigation water supplies are derived principally from snow melt, estimates of seasonal runoff are made from measurements of the winter accumulation of snowfall at selected mountain sites. The Department recognized the need for providing basic data for predicting the water supply available in a given watershed for irrigation and other purposes. This information is needed to provide for the seasonal planning of irrigation operations. In years of short water supply, forecasts of seasonal water

supplies furnish a reliable basis for necessary modifications in cropping and irrigation plans. On the other hand, in years of heavy snow pack, accurate forecasts of increased water supply make it possible to plan for bringing additional land temporarily under irrigation. The snow content is also an important factor in reservoir regulation for flood control purposes, as well as forecasting major flood events on unregulated streams. Engineers of the SCS have developed and perfected streamflow forecasting from snow pack measurements.

Water Laws

The increase in use of water nationally for domestic, industrial, agricultural purposes in the past 10 years coupled with drouth conditions of major proportions have emphasized the need for adequate evaluation and regulation of this valuable resource. Many states are reviewing their water laws with a view of making changes to meet existing and future conditions. Development of water for agricultural purposes cannot proceed effectively until the user has reasonable assurance that the appropriation is valid and cannot be preempted by some other user. The SCS is cognizant of this need and maintains a small staff who, on request, cooperate with interested groups in insuring that the interests of agriculture are fully considered in making recommendations for new or corrective legislation. Presently a large portion of the assistance rendered is in the east where present laws generally follow the doctrine of riparian rights. This law is not well adapted to the appropriation and regulation of water for agricultural use.

Watershed Operations

Project formulation arises out of the problems and desires of the people to be served. Careful definition of the objectives of the project and the preparation of tentative possible solutions, in cooperation with the affected people, is the first job in which the engineer plays an important role. Social and political factors will eliminate some of the possible solutions. The problem resolves itself into finding an economical and practical solution, with a favorable benefit-cost ratio, that is acceptable to the people.

While watershed projects are generally considered to be developed primarily for flood prevention—drainage, irrigation, stabilization of annual streamflow, recharge of ground water, community-water supply for agricultural purposes, and non-agricultural uses such as municipal or industrial water supply, recreation, power, fish and wildlife improvement, pollution abatement by streamflow regulation, and saline water-intrusion control are authorized. Storage may be incorporated in single-purpose or multiple-purpose structures which are an integral part of a plan for the protection and improvement of a watershed. Works of improvement authorized for purposes of flood prevention include: floodwater retarding structures; clearing, straightening, and enlarging stream channels; levees, debris basins, floodways; diversions, grade stabilization, and streambank stabilization. Thus the engineer encounters a wide variety of engineering problems in developing project work plans and detailed construction plans and specifications.

Alternate plans for the watershed are considered in the preliminary study. Available data in the form of published topographic maps, aerial photographs, soil surveys, rainfall and runoff data, geologic maps, previous studies and other information may need to be supplemented by additional data to permit logical selection of the most sound proposals for more detailed study.

Horizontal and vertical control are established in the watershed with considerable detail at the proposed sites of work. Levels are run and base lines and traverses completed as a framework for detailed topography, cross sections and profiles.

The engineering geologist studies the general geology of the area, directs the making of borings and test pits, and determines the characteristics of the earth materials to be encountered in and available for the proposed work. The geologist cooperates with the design engineer in evaluating the suitability and usefulness of the earth materials.

Other engineers study the soils, cover, slope, drainage pattern and other pertinent runoff producing characteristics of the watershed. From these studies the peak rates and associated volumes of runoff for storms of varying frequency, the total annual yield from the watershed for both wet and dry years, and the hydrographs of runoff for the various storms are developed. These hydrographs and associated data serve as a base for making the economic analysis of the damaged areas.

Detailed tests of the earth construction materials and of the foundation materials are made in soil testing laboratories. The soil is classified under the Unified System, and shear strength, compressibility, permeability, compaction tests to determine densities under varying amounts of moisture, test for dispersion and soluble salts are made. The analyses are interpreted for the guidance of the engineers who will design the works of improvement.

Planning engineers will prepare preliminary layouts and cost estimates of the various proposals based on the data at hand. From these studies and considering the wishes of the people, a final work plan is prepared.

The next step is to check and refine the work plan into a set of detailed construction plans. This involves a thorough knowledge of hydraulics of spillways and open channels, soil mechanics as applied to the design of earth embankments and channels, structural design and detailing. Final quantities are computed and the engineer's cost estimate is prepared. Specifications are prepared for each item of work and then the construction engineer and the contractor take over to complete the job.

The completed work must be evaluated in operation to define improvements in engineering procedure and design criteria.

Retarding Dams

The retarding or detention dam is the structural measure most widely used in the watershed program. It serves to store floodwater temporarily and release it at a controlled rate. For any given watershed a system of retarding dams may be required to control the runoff to the extent feasible to reduce inundation and siltation of low-lying lands.

A study of the floods, as they affect agricultural lands, shows that on the average the major portion of the flood damage is caused by small floods of a size that occurs more frequently than once in 10-15 years. Most systems are designed to afford protection from this class of storm. The value of the land, the hazards to roads, bridges, building and urban interests and safety

of the structure are factors that are given full consideration in determining the design storm for which protection will be provided.

The typical retarding dam used by the Soil Conservation Service has some features that depart from previously accepted practices in the field of earth dam design. This structure was pioneered and developed by the SCS during the past 15-20 years. The experience gained in this period has been an important factor in establishing the criteria governing the design of retarding dams.

In order to give an idea of the size of structures being built, an analysis was made of plans covering 324 structures built or under construction prior to June 30, 1954. The analysis was based on representative projects and gave the following information:

Average cost of dams	$26,200
Average height	33 feet
Average volume of embankment	51,000 cubic yards
Average total storage capacity	560 acre feet
Average size drainage area above dam	1,350 acres

Each structure has an uncontrolled outlet designed to provide for a discharge that will give the desired degree of protection downstream. Based on plans prepared to date, the discharge rates of outlets range from 4 to 15 cubic feet per second per square mile of drainage area.

Energy dissipation structures are not normally provided at outlets less than 36 to 42 inches in diameter. The outlet is extended below the downstream toe of the dam and supported on a concrete pier carried to a solid foundation. The scour hole formed by the falling jet or excavated at the time of construction, is located far enough below the dam to give adequate protection. This type of outlet is called a cantilever outlet.

The retarding pool is designed to store a 25-year or greater frequency storm depending on erodibility of the material in the spillway and downstream hazards. An earth or rock spillway designated as the emergency spillway is used to discharge flows in excess of the capacity of the primary spillway plus reservoir storage. The 25-year frequency is the minimum frequency established for earth spillway operation and is used at those sites where the spillway contains good erosion-resistant soil.

The earth spillway is cut in original ground and may be placed in one or both abutments. The spillway is designed to carry the flow from the design storm around the end of the dam and discharge it into the channel below. The minimum design storm has an occurrence of not oftener than once in 100 years. The spillway proper is designed to carry the design discharge at a velocity that will permit vegetation to provide for reasonable protection against erosion. Extensive studies made at the Stillwater, Oklahoma Hydraulic Laboratory, of channels vegetated with different types of cover show the safe velocity to range from 3-7 feet per second. Based on experience over a 20-year period, this type of spillway has been found to operate effectively.

Group Enterprises

Engineering activities in the Soil Conservation Service can be divided into two broad categories, assistance to formal and informal groups and assistance

to individual farmers and ranchers. While group work represents a relatively small part of SCS operations, it does require a considerable part of the engineering work load. Much of the group work is concerned with watershed development and the rehabilitation of existing irrigation and drainage projects.

The SCS recognizes that many conservation problems can only be solved by giving full consideration to watershed or community needs. In many areas the solution of group problems is a prerequisite to the development of adequate soil and water conservation plans for individual farms and ranches. For example, a drainage system needed to permit application of conservation measures to an individual farm cannot be developed until an adequate outlet is available. Similarly, a proper distribution system for an irrigated farm cannot be developed until an adequate water supply is made available. In working with group enterprises, conservation plans are required for the farms affected by the enterprise.

It is recognized that some of the engineering work involved in group enterprise operations is similar to work that is handled by some private engineering firms. When this category of work is encountered the SCS recommends that the district obtain the services of private engineers whenever possible.

The engineering services of ths SCS can best be utilized in the development of work plans which establish the over-all project feasibility, the establishment of functional requirements of the structure to meet the conservation need, formulating the basic engineering criteria, and providing a reliable cost estimate. Based on this information the sponsoring group can reach a decision as to whether or not the project is to be built. If a favorable decision is reached the work plan will serve as a basis for the development of construction plans and specifications. It is the policy of the SCS to cooperate with private engineers retained by the district or group to assist in developing plans and specifications to meet the conservation requirements. Due to shortage of consulting engineers familiar with this class of work, the general lack of engineers in many areas, and the desire of many districts to avail themselves of governmental services, it has not been possible to utilize outside help extensively. The SCS is committed by law to give technical assistance to individuals and groups on request. When outside help is not available, assistance must be given to insure that the conservation program moves ahead in keeping with the wishes of the soil conservation districts through which SCS operates. The SCS has pioneered the conservation aspects of engineering and largely through its efforts the field of engineering and contracting as it relates to conservation aspects, agriculture has greatly expanded during the past 20 years. The job is of a magnitude that the united efforts of all will be required to get it done.

Drainage and Irrigation

Engineering activities in the field of drainage and irrigation are multiplying rapidly. Authoritative sources estimate that a total of 29.5 million acres of land was irrigated in 1955, 27 million of which is contained in the 17 western states.

Percentage wise this represents a 10 percent increase in the west over the preceding 5 years and a 70 percent increase in the 31 eastern states. The magnitude of the increase in the east can be better understood by comparing

the total in the two areas and considering that of the 2.5 million acres under irrigation, 2.0 million acres are in 3 states, Arkansas, Mississippi, and Florida.

Long-time forecasts indicate the total area that can feasibly be irrigated is in the neighborhood of 40 million acres. This represents a long-time increase of approximately 10 million acres, possibly half of which may occur in the east.

Similar figures for drainage show there is a total of 87 million acres presently in organized drainage enterprises and an additional 90 million acres of wet lands. It is estimated that of the 87 million acres in enterprises, 29 million acres need improved drainage. Out of the 90 million acres of wet land, 20 million acres can be feasibly drained based on the present economy. In the irrigated sections of the west there are 8 million acres of land requiring some degree of drainage, thus approximately 57 million acres of land will need drainage assistance. These statistics indicate the need for engineering services in the field of drainage and irrigation.

The Service's major responsibility in the field of drainage and irrigation is to assist farmers and ranchers in developing and applying conservation plans. In assisting in the development of a farm conservation plan for irrigation, the engineer must (1) determine the adequacy of the water supply to meet daily and seasonal requirements, (2) collaborate with the soil scientist to determine suitability of the land for irrigation, (3) plan the method of irrigation best adapted to crop and site conditions, (4) lay out an economical and efficient farm distribution system, (5) develop an adequate water management program, (6) determine the cost and increase in production, and (7) develop an adequate maintenance program. Engineering plays an important part in the development and application of the irrigation and drainage works.

The SCS has pioneered in the development of a coordinate approach to the irrigation and drainage of farm land. It has steadfastly recognized that soil, water, and plants have a basic relation that is inseparable. It has taken a scientific approach to the use and disposal of agricultural water. Research and field trials and experience have provided basic data used in planning of the conservation aspects of drainage and irrigation.

Irrigation

As an aid in planning the engineering aspects of irrigated land, SCS has developed what is termed an irrigation guide. It is a handbook that is used by the conservationists to develop the irrigation plan for a farm. The guides specify the proper method of irrigation, length of run, size of irrigation stream, amount of water to be applied, rate of application, etc. for the crops, soil types and climatic conditions in a given area. The guide provides a scientific approach to planning irrigated lands. The SCS is constantly making field evaluations to gather data that will be used in improving and enlarging the scope of the guides. Irrigation guides covering most of the irrigable soils in 40 of the 48 states have been prepared.

Irrigation must be considered a way of farming. In most of the west where irrigation is practiced, rainfall is so sporadic and limited that irrigation water is applied on the basis of crop needs irrespective of weather. In the humid areas there is a tendency to think of irrigation as a crop insurance, used only when rainfall is lacking. Major reliance on rainfall usually causes

irrigation water to be applied "too little and too late." The yields under such a plan often will be little more than those without irrigation. Many analyses of rainfall records correlated with soil type and crop requirements show that soil moisture deficiency occurs frequently enough in the humid regions to make irrigation necessary nearly every year in order to obtain maximum crop yields. In order for irrigation to pay its way, the system should be managed to provide for optimum production.

Full consideration must be given to the hazards of water erosion caused by rainfall on irrigated lands, in the humid area. Conventional methods of irrigation of sloping lands in the west are not successful in humid area where runoff due to rainfall occurs at frequent intervals. Provisions must be made to develop a system that will safely dispose of runoff created by rainfall. All irrigation systems must also provide for drainage of excess water. Irrigation may aggravate the drainage problem on poorly drained soils. Well drained soils may become waterlogged if too much irrigation water is used.

A few statistics will illustrate the volume of work on which the Service has rendered assistance. Technical assistance on land leveling which is a good indication of the improvements made in irrigation methods and distribution systems increased from 251,000 acres in 1948 to 493,000 acres in 1955. The SCS is currently giving assistance on land leveling operations on approximately 500,000 acres of land annually. Leveling land is a basic step in applying water uniformly to the land by gravity irrigation. It also assures good drainage which is a necessary adjunct to any well designed distribution system. Records further show assistance was given on 6,990 sprinkler irrigation systems in 1954 and 8,590 systems in 1955, 2,922 irrigation reservoirs in 1954 and 4,160 in 1955, and in improving the application of water on 1,032,000 acres in 1953, and 1,805,000 acres in 1955.

Drainage

The problems involved in planning the conservation aspects of drainage of farm lands is quite similar in principle to those outlined for irrigation. The main difference is that drainage involves water disposal—either surface or underground—to provide a moisture level that will make for optimum production. Drainage is needed in the humid areas and in arid areas where irrigation is practiced.

Assistance rendered by the SCS is confined to the rehabilitation and improvement of drainage works providing for drainage of lands presently being used for agricultural production. Because of agricultural surplus, assistance is not given in the development of drainage works, the primary purpose of which is to drain land not previously in cultivation.

Drainage work involves open ditch systems, underground tile systems, control works to regulate the water table level based on crops grown and pumping plants to provide outlets for low level areas. Land leveling or smoothing is also coming into prominence as a drainage measure. Forming the land surface to provide drainage eliminates the need for many field ditches, simplifies farming operations, and insures more uniform drainage resulting in optimum crop production.

The Department recognizes the importance of wildlife resources in the development and application of the drainage program. The soil and water

conservation program of SCS and other departmental agencies are very effective in improving habitat and increasing the wildlife population.

Drainage works form artificial tributaries of natural stream systems. Proper drainage can only be obtained by developing a channel or ditch system that has the capacity and depth requirements needed to provide for sound agricultural use. In many areas difficulties are encountered in finding an adequate outlet. This problem has been magnified in recent years through the expansion of our national and state system of highways. Major highways traverse wide areas where the agricultural needs have not been fully developed. One of the most critical problems relates to the elevation at which highway culverts are established. In planning these highways, full consideration should be given to the needs of drainage.

The cost of bridges and culverts on multiple lane highways make it difficult to make any modifications after construction is complete. In most cases the cost of culverts is not materially affected by the variation in elevation needed to meet drainage requirements. Careful consideration of agricultural drainage needs in highway construction will improve the long-time agricultural economy of the area.

Erosion Control Practices

The other aspects of conservation engineering relate to what is termed erosion control practices which involve terracing, diversions, water spreading, stock-water development, contour furrowing, contour farming, and strip cropping to control erosion and conserve water, planning waterways to serve as disposal systems for excess runoff, and planning grade stabilization and gully control measures to reduce downstream siltation and provide a satisfactory water disposal system.

Engineering in the Service is unique in the sense that because of the nature of the work, the engineer usually has an opportunity to follow a job through from its inception to completion. While there is much opportunity for specialization a majority of the engineers enter into the planning, layout, design, and supervision of construction of projects or jobs with which they are associated. This factor coupled with the working relationship established with the other technical divisions gives the engineer broad experience and training in carrying out project type operations. A real sense of satisfaction is gained in participating in all phases of engineering operations.

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CAN EVAPORATION LOSSES BE REDUCED?

G. Earl Harbeck, Jr.[1]
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ABSTRACT

The evaporation loss from surface reservoirs is a major item in the water budget of the Western States. A number of methods of minimizing evaporation losses are described. Two methods that appear to warrant intensive study are the use of a monomolecular film, such as hexadecanol, on the water surface and the use of ground-water reservoirs for storage.

The desirability of reducing evaporation losses in the Western States has received increasing attention in recent years because of the increase in the demand for water and the decrease in the supply available during the current drought. The increase in demand for water is attributable to many factors, among which the most important are (a) the increase in population in the far Western States since the beginning of World War II, (b) the up-surge in industrial activity in the West, (c) the increase in the acreage of irrigated lands, and (d) the increase in the per capita use of water resulting from a higher standard of living. The current drought in the Southwestern States began in some areas as early as 1942; in other areas it did not become serious until 1953. For example, except for 1952, precipitation and runoff have been critically low in Utah for the last 7 years (U. S. Geological Survey, 1956); this is somewhat typical of conditions in many parts of the West. The drought is not equally severe in all parts of the Southwest, but water supplies have in general been notably deficient in many areas during recent years.

Withdrawals of surface water for rural, municipal, industrial, and irrigation uses in the 17 Western States in 1950 was estimated by MacKichan (1951, table 1) to be more than 70 million acre-feet per year. Of this, more than 90 percent was for irrigation use. A part of the water withdrawn

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1. Hydr. Engr., U. S. Geological Survey, Denver, Colo.

appeared as return flow and was reused, so that the amount of water used consumptively in industry and irrigation was substantially less than the 70 million acre-feet withdrawn.

Net water loss by evaporation and by transpiration from vegetation along water courses in the 17 Western States has been roughly estimated to be more than 30 million acre-feet per year (U. S. Geol. Survey, 1954, p. 1). To obtain a more reliable figure of this loss, the Geological Survey is now making a study to determine the volumes of water dissipated by evaporation in each State and in each major drainage basin. Determining average surface areas of the major lakes and reservoirs is relatively simple, but estimating the surface areas of the myriad stock ponds that have been built in the West in recent years presents some difficult problems. For the purposes of this discussion it need be pointed out only that the evaporation loss from reservoirs is a major item in the water budget of the Western States, and anything that can be done to reduce evaporation losses will be of great benefit to the region. Not only will the total supply of water available for use be increased, but the quality of that water will be improved, for evaporation removes only pure water.

Many methods of reducing evaporation losses from reservoirs are known. Project planners and designers are well aware of the desirability of a reservoir having a minimum of surface area for a specified capacity. A small increase in height in a dam may result in a relatively large increase in storage capacity, but if the surface area is increased disproportionately thereby, a net loss in water may result because of the greatly increased evaporation loss. Evaporation losses are only one of many factors to be considered in designing a dam and reservoir, and other considerations may dictate a compromise.

Some measure of control of evaporation losses from a reservoir can be obtained through operational procedures. Losses could be kept at an absolute minimum by keeping the reservoir empty at all times, but the purpose of constructing the dam would be defeated thereby. An operational schedule providing for a full reservoir in winter when evaporation losses are low and an empty reservoir in summer when losses are high would reduce evaporation losses but unfortunately such a scheme is generally not practicable in the West, where much of the runoff occurs in the spring as a result of the melting of the mountain snowpack. Some advantage can be gained by an operational plan designed to minimize the area exposed to evaporation during the hot summer months, but frequently other requirements, such as scheduled releases for irrigation or power, are of far greater importance, and little attention can be paid to minimizing evaporation losses.

If a series of reservoirs on the same stream are operated as a unit, certain procedures can minimize evaporation losses from the system. Savings will result from storing water in the shallow reservoirs during the winter and concentrating the reserves in the deep reservoirs during the summer. Other considerations, such as power or irrigation release schedules, may prevent operation of the system in such a manner as to gain the maximum benefit insofar as evaporation savings are concerned.

Another method of reducing evaporation losses is to dike off shallow areas. According to Freese (1956, p. 47, 48) it was found economically feasible to construct a dike at Lake Worth, Tex., to eliminate 112 acres of water surface. Plant life and transpiration losses were reduced on an area of 44 acres.

Because evaporation increases with water-surface temperature, summer

evaporation losses could be reduced if it were possible to skim off only the warm surface water from a reservoir, thus reducing the water-surface temperature. The potential saving in evaporation depends on the efficiency of the skimming process. Temperature gradients in the surface layer are often steep, so that the warm surface layer may be thin. Although the variation in temperature with depth may be large, the resulting density differences are extremely small. It has been shown (Gartska et al., 1957) that if the fluid in the reservoir were homogeneous, outflow over a weir near the surface would contain equal contributions from all depths of the reservoir. Laboratory experiments with non-homogeneous fluids (U. S. Bureau of Reclamation, 1956) showed that withdrawals of water over a weir would be composed of not only the surface water equal to the depth of flow over the weir but also contributions from underlying strata. Thus the saving in evaporation would be less than if it were possible to actually skim the warm surface water. If a dam has outlets at different depths, the use of the outlet nearest the surface will result in some saving in evaporation, but it would be partly offset by the increase in evaporation from the stream below the reservoir.

The use of oil films to suppress evaporation has received considerable attention in past years. Water molecules diffuse slowly through an oil film, and a thick film may reduce evaporation considerably. The application of an oil film preventing evaporation of water has been patented by Nelson (1939) but this method has not been widely used. It has been found that in some instances an oil film is damaged by both wind and dust (Mansfield, 1955) and that because an oil film is rigid, it does not heal itself if it is broken by wind or wave action. Dust particles settling on an oil film may act as capillary wicks and transfer water through an otherwise impermeable film.

Leon Fine and Associates have applied for a patent for a "Reservoir water covering structure," which is a cover structure made of plastic. No information is available as yet concerning the cost of such a plastic film or whether the inventor considers it suitable for use in large reservoirs.

Small reservoirs used for storage of filtered water are usually provided with roofs, but these are considered more as a protection against air-borne pollution rather than as a means of reducing evaporation. Assuming that filtered water is worth 15 cents per 1,000 gallons, and that net evaporation loss from the reservoir is 4 feet per year, Freese (1956, p. 50, 51) computed that the annual cost of a roof would be $6,000 per acre whereas the water saved would be worth only $200 per acre of water surface.

According to Thomas (1951, p. 12), "Few ground-water reservoirs are yet utilized to store flood flows for later use, and they are generally not even considered in river-basin flood-control and storage programs. Yet many have a capacity far greater than the largest artificial reservoirs. They can provide holdover storage with minimum loss of water by evaporation and with minimum loss of productive land. Some certainly deserve a far larger place in plans for complete water development, but cannot attain that place until hydrologic knowledge is sufficient to show the way to successful manipulation of ground-water storage." As the number of available sites for large surface reservoirs decreases, increasing attention will doubtless be paid to the use of underground reservoirs. Wide alluvial valleys may eventually be utilized to a much greater extent for ground-water storage than they now are. The subsurface conditions at most dam sites do not provide storage for large volumes of ground water. A good site for a surface reservoir is usually a

poor site for a ground-water reservoir, and vice versa. Since most of the better dam sites in the Western United States have been utilized, a comprehensive investigation of possible sites for ground-water storage appears advisable.

In recent years increasing attention has been given the possible use of a monomolecular film for suppressing evaporation. The early work of Rideal (1925), Langmuir and Langmuir (1927), Langmuir and Schaefer (1943), and other investigators indicated that certain monomolecular films were effective in suppressing evaporation, and that the substance most likely to be useful was hexadecanol. Hexadecanol, also known as cetyl alcohol, is not an alcohol in the ordinary sense of the word; it is a wax. According to LaMer (1956) the alcohols spread because they contain an OH group in each molecule. The OH group is attracted to the water molecules, which also contain an OH group. If the monomolecular film is compressed, the long-chain molecules are packed tightly together and stand erect. For a water molecule to escape, it is necessary for it to thread its way between the compressed molecules of the film.

The foregoing explanation is admittedly incomplete, but an excellent review of the history of the use of monomolecular films for suppressing evaporation, a clear explanation of the theory, and an extensive bibliography are contained in a paper by Moran and Gartska (1957). There follows a brief outline of the work of other investigators.

W. W. Mansfield, an Australian physical chemist, was the first to appreciate the potential practical value of the use of a monolayer for suppressing evaporation from reservoirs. He showed that hexadecanol will form on a water surface a monomolecular film that is resistant to the action of dust and wind. Moisture may be transmitted through an oil film by dust particles acting as capillary wicks. Hexadecanol forms a fluid film, which contracts and expands with wave action, while rigid monolayers are easily broken by waves. Mansfield calculated that the solubility of hexadecanol in water is 0.0002 parts per million.

Mansfield experimented with several forms of hexadecanol, for the rate at which molecules leave solid hexadecanol depends primarily on the perimeter of the solid which is in contact with the water surface. He found that powdered material aggregated on the surface of the water within a few days, thus reducing the perimeter in contact with the water. Beaded hexadecanol confined in a wire mesh screen supported by a float was used in later experiments.

Mansfield emphasized that much research remains to be done. From his experimental work he was unable to predict the effective life of a single treatment. The results of his experiments on a lake having a surface area of 2,100 acres were disappointing. Only when winds were light did the treatment seem to reduce evaporation significantly. In this experiment the film was generated by spreading of a solution of hexadecanol in a volatile solvent as well as spreading from the solid.

In a personal communication, Mr. F. Grundy of the East Africa Meteorological Department, Nairobi, Kenya, described his experiments using a hexadecanol solution in kerosene with the addition of 3 percent of a spreading agent. The solution is applied along the upwind perimeter of a reservoir, either manually or from dosing tanks. Because of the apparent deterioration of the film with time, Grundy recommended continuous application instead of intermittent dosing.

Because of the tremendous potential economic worth of a successful scheme for reducing reservoir evaporation, the use of a monomolecular film has been

given considerable attention in the United States during the last several years. Among the organizations actively engaged in studies of evaporation suppression are the U. S. Geological Survey, U. S. Bureau of Reclamation, Southwest Research Institute, and the Illinois State Water Survey Division. The work done by the U. S. Bureau of Reclamation has been described in a paper by Moran and Garstka (1957). The investigations of the Illinois State Water Survey Division have been described by Roberts (1957).

The studies by Southwest Research Institute began in 1955 under the sponsorship of a group of public agencies and private corporations, with the Texas Board of Water Engineers acting as contracting agency for the sponsors. A review of current literature on evaporation control was made, and a bibliography was compiled. Laboratory tests of various compounds were then made. The test apparatus, as described by Dressler (1956, p. 70) consisted of an insulated metal trough filled with water whose temperature was maintained at 30° C. Eighteen battery jars containing distilled water were placed in the trough. One or more jars were left untreated for control purposes, and the rest were treated with the chemical compounds being tested. Dried air was blown over each jar at a speed of approximately 0.1 mile per hour. Water levels were maintained at a constant height, and the volume of water required for replenishment was measured to determine evaporation loss from the jar. About 150 potential evaporation retardants were tested in the laboratory, and those giving the largest reduction in evaporation were tested further in the field. It was found that most samples of hexadecanol and octadecanol gave good results in the laboratory, although there was considerable difference between the results obtained using the same compound furnished by different manufacturers.

The first field tests were made on two 10-foot diameter metal stock tanks. A preliminary test was made with both tanks untreated to demonstrate that there was no inherent difference in natural evaporation losses from the two pans. The evaporation suppressant was applied to one tank and the other left untreated. Tests made in June 1956 indicated that octadecanol was superior to hexadecanol, both in water saved and in film life, during the summer in South Texas. Although both compounds caused substantial reductions in evaporation during the first few days, the efficiency of the film decreased rapidly, and was negligible after 8 or 9 days.

Measurements of evaporation both with and without a film were made by the U. S. Geological Survey on a 3-acre ranch pond near Southwest Research Institute. The energy-budget method was used to measure evaporation from the pond during a 3-week calibration period, and for three other periods when a film was applied. Provisional results indicate that a reduction in evaporation of 4 percent was achieved during a 10-day period in August when a dose of 2.2 pounds per acre of octadecanol was applied; a reduction of 9 percent was achieved during a 10-day period in September when a dose of 20 pounds per acre of octadecanol was used; and a reduction of 18 percent was obtained during a 3-week period in October when a dose of 20 pounds per acre of hexadecanol was used. For the last test the pond water-surface temperature was computed to be 3.3° F higher than it would have been if no film had been applied.

The figures of evaporation reduction are necessarily classed as provisional pending tests of the effect of a monomolecular film on certain physical characteristics of a water surface. For these computations it was assumed that the film did not affect the reflectivity (for short wave radiation) of the

water surface, nor did it affect the absorptivity or emissivity of the surface for long wave radiation. Admittedly these assumptions have not yet been proved, but it is believed that the error introduced thereby is negligible. The Geological Survey plans to determine the effect of a film on these physical characteristics of a water surface, but the tests will not be made until there is general agreement as to the compound to be used and the form in which it is to be applied.

In computing evaporation by the energy-budget method, the Bowen ratio, which is the ratio of the energy conducted to the atmosphere as sensible heat to the energy utilized for evaporation, is commonly used because it is difficult to make direct measurements of the energy conducted to the atmosphere. The Bowen ratio is not applicable if the water surface is covered with a film. Before a reservoir is treated a calibration period is required to determine an empirical constant necessary to compute the energy conducted to the atmosphere after the film is applied. During the calibration period the Bowen ratio is valid, and may be used to compute the conducted energy term. An empirical relation between conducted energy thus computed and the product of the wind speed and the air-water surface temperature difference is then determined, so that after the reservoir is treated, the conducted energy term can be computed from the wind speed-temperature difference product, and the Bowen ratio is not used. The rise in water-surface temperature can be computed by using a combination of the mass-transfer and energy-budget methods (Harbeck, 1953).

Many investigators have commented on the apparent deterioration with time of a hexadecanol film. It seems clear that some of the material is actually consumed by microorganisms in the water. It remains to be seen whether the rate of consumption will prove sufficiently great to make the use of a hexadecanol film impractical because of the large amount of replenishment material that may be needed. Southwest Research Institute has experimented with copper compounds in an effort to find a bacteriocidal or bacteriostatic agent which, when mixed with hexadecanol, will reduce the biochemical oxidation rate.

The toxicity of hexadecanol has been investigated by the Robert A. Taft Sanitary Engineering Center of the U. S. Public Health Service. In a statement dated February 12, 1957, Dr. Bernard B. Berger, Chief, Water Supply and Water Pollution Program stated "...... in view of the lack of direct evidence of hazard to health upon ingestion of the above components, and certain evidence favoring the view of their probable innocuousness, and in view of the improbability of ingestion of any but extremely trivial amounts of the preparation as a result of the method of use, it does not seem reasonable to anticipate that any hazard to health from its use for the purpose, and under the conditions stated, would result to any individual, even though exposure were to be for the lifetime of the individual."

The use of hexadecanol for the suppression of reservoir evaporation offers considerable promise as a means of conserving available supplies of water in the West. It should be emphasized that much remains to be learned, particularly with respect to methods of applying and maintaining a film, and techniques for increasing the life of the film. A method of determining the areal extent of coverage of the film is also needed. Techniques have been developed for detecting the presence of a film at a particular point, but some other method is needed to show which areas of a large reservoir are covered. Perhaps an optical method will be found practicable.

Among the many methods of reducing reservoir evaporation losses heretofore described, the two methods that appear to warrant intensive study are the use of a monomolecular film, such as hexadecanol, and the use of ground-water reservoirs for storage. The success of the film method depends principally upon the solution of a number of technical problems. The test made in Texas in which a saving of 18 percent in evaporation resulted from the use of 20 pounds of hexadecanol per acre cannot be considered a practical success. If better techniques of application and maintenance can be found so as to reduce the apparent consumption of the material by microorganisms, the use of a monomolecular film may prove to be a practical method of suppressing evaporation. On the other hand, before ground-water storage reservoirs can be successfully used on a large scale, there are both technical and legal problems to be solved. Again, the technical problems do not appear insolvable, but comprehensive hydrologic studies are needed to evaluate the potentialities of ground-water reservoirs. The solution of the legal problems may take longer, but as our knowledge of the water resources expands, many defects of existing water laws can be overcome (Thomas, 1951, p. 13). Clearly, further study is indicated of the use of monomolecular films and ground-water reservoirs for the conservation of water.

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WATER SUPPLY VERSUS IRRIGATION IN HUMID AREAS[a]

M. C. Boyer,[1] M. ASCE
(Proc. Paper 1500)

SYNOPSIS

Man requires water for urban waste removal, fire protection, and industrial processes; and for agriculture, where natural precipitation is undependable. To insure maximum beneficial use of the supply, watershed inventories are necessary—to determine present and future needs and recommend maximum beneficial use. White River Basin, Indiana, is so inventoried.

INTRODUCTION

Without abundant quantities of water at Man's disposal, civilization as we now know it could not long exist. Water removes the wastes from the household, provides protection from fire, is required in large amounts in many industrial processes, and makes up the moisture deficiencies for growing crops in those regions where natural precipitation will not sustain plant growth.

The installation of sewer systems for the removal of household wastes probably received its greatest impetus with the advent of the water closet, once described by a Chinese scholar as the most useful invention of western civilization. Household use of water increased rapidly after that time and in recent years is spurting upward as homeowners install modern bathing facilities, automatic washers for clothes and dishes, and grinders for the disposal of garbage through the sewer system.

Water has long been used to extinguish fires. In earlier times, the quantity that could be put on a fire depended on the efficiency of bucket brigades or the

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1. Hydr. Engr., Indiana Flood Control and Water Resources Commission, Indianapolis, Ind.

gravity pressure in supply mains. Within the last half century there have been developed efficient mobile pumping apparatus which can take from the water mains much larger quantities than the mains could deliver under their own normal pressure and can throw the water much farther from the nozzles. A number of such apparatus, converging on a major fire, places very large demands on the water supply.

Many industrial processes require large amounts of water for cooling, washing, and treatment of the product. Generally, little of this water is consumed, most is returned to streams or lakes, higher in temperature or containing pollutants.

The production of crops through irrigation is one of the very early uses to which Man has put water. In India, canals built before the Christian era still convey water to arid regions of the Punjab. Long before the time of Columbus, highly civilized inhabitants of the Andes transformed areas of barren desolation into crop-producing fields by terracing, fertilizing, and irrigating. Many of these all but imperishable hanging gardens are cultivated today by descendants of the ancient Incas. Irrigation began nearly as early in the southwestern United States. It is today an essential part of western American life.

In recent years, with the advent of light-weight pipe and small, efficient engine-driven pumps the use of water for irrigation in humid regions, where during most years crops will grow unwatered, but will produce much more bountifully when artificially watered during periods of drought, has grown by leaps and bounds. It is this last use of water and its effect on the supplies for other uses that must be evaluated and regulated as necessary to obtain the greatest benefit from the waters of a basin.

Water Use Today

Municipal Water Supply

Foremost among the uses of water in modern civilization is for municipal supply. Cities and towns require potable water in ample quantities to meet the needs of domestic uses, waste disposal, fire protection, and urban industries. Heavy demands are being placed upon the water resources of the nation to provide adequate municipal supplies. In 1953 there were an estimated 16,000 public water-supply systems in the United States, serving 106 million people.(1) Of these, 552 served cities with a population of 25,000 or more and supplied the needs of nearly 80 million people. The average output of the 16,000 systems was 11.8 billion gallons per day. This is equivalent to an average use of 148 gallons per person per day, as compared with 140 to 150 gallons per person per day in 1945, for cities of 10,000 and over.(2)

Municipal Waste Disposal

A large part of the water which a city takes into its supply mains is discharged as waste through its sewer system. In fact, in many cities infiltration and the intrusion of storm water, accidental or otherwise, produce a sewer out-flow larger than the city's intake of potable water. This sewage is treated for the removal of solids and reduction of the biochemical oxygen demand and then released to a lake, watercourse, or the ocean, to be removed from the vicinity and rendered innocuous by the action of dissolved oxygen and sunlight.

In spite of the deleterious effects of wastes discharging into natural waters,

even now not all cities and industries provide adequate treatment and several provide none. Of some 9,000 sewer systems in operation in 1955 (compared with 16,000 waterworks), only 6,000 discharge through a treatment plant. Nearly two-thirds of the nation's population is served with public water supplies and one-half with sewage collection facilities, but only one-third with sewage treatment plants.[3]

Steam-electric Power Generation

Steam-electric power generation is one of the greatest industrial users of water. Plants as now designed remove by condenser cooling 5,000 BTU of heat from spent steam for each kilowatt-hour of electric generation. The quantity of cooling water required depends upon the efficiency of the condensers and the permissible increase in cooling water temperatures. The amount varies, but averages about 1,000 second-feet for a plant with a rated capacity of 1 million kilowatts, operating at normal load.

In 1955 the total capacity of all electric generating stations operated for public use in the United States was approximately 114 million kilowatts. They produced 546 billion kilowatt-hours during the year.[4] By contrast, in 1945, the installed capacity was 50 million kilowatts and the production 222 billion kilowatt hours.

Other Industries

There are a great number of diverse industries drawing upon the water resources of the nation. Their needs are varied, but their consumptive uses are generally low. Nearly all the water is discharged to the ocean, a lake, or a stream, except in some instances of ground water pumped for cooling being returned to the ground. Nearly all industrial wastes are polluted to some degree or warmed and additional water must be provided to remove them in the same manner as sewage is removed. Accurate figures on the water needs of industry are not available, but it is estimated that industries other than electric generation require about 10 billion gallons per day.

Agriculture

The use of water for the irrigation of crops is an industry which is located primarily in the 17 western states, where without irrigation few crops could be produced. Irrigation in the humid regions is not essential, but because of the decidedly beneficial effects, primarily during periods of deficient rainfall, it is being more widely practiced each year. The estimated total acreage under irrigation in the United States during 1954 was 29,500,000 acres, of which 20,500,000 acres were in the west, leaving 9,000,000 acres in the humid regions of the east.[5] In 1939 the land under irrigation in the humid regions was 2,300,000 acres. The increase from 1939 to 1954 amounted to 450,000 acres per year, a measure of the importance which is being attached to irrigation in those regions where natural precipitation will generally suffice to produce a crop.

Regional rate of growth of irrigation in humid areas is well exemplified by studies made at Purdue University[6] which show that:

> From 1940 to 1950, the number of irrigated farms in humid areas increased 75 percent, and the number of acres irrigated increased about 283 percent—most of this increase occurring from 1946 to 1950. A

survey in Virginia indicated that irrigated farmland increased 700 percent from 1949 to 1954. Data from Tennessee indicated an increase of at least 2100 percent from 1949 to 1954. Even in Iowa, which is usually confronted with drainage problems, the number of farmers using irrigation increased from 76 to 136 from 1949 to 1954. Farmers irrigating in Illinois increased from 139 to 266 from 1951 to 1954. In all humid states, irrigation on farms has increased about 70 percent between 1949 and 1954. Sprinkler irrigation is well established also in Canada, where some 3,500 systems were installed up to 1951.

Thus, even though irrigation is an infant farming practice, and the percent of lands irrigated is quite small; its growth has been phenomenal. It is this growth, and its potential use of water, that is disturbing to other water users.

Water Use in the Future

Trends in Population Growth

The population of the United States is growing rapidly. A rising birth rate and continuing elevation of average age of death are working together to keep filling our nation with people. Most of this increasing population is settling in urban areas and contiguous suburban developments for the urban dwellers who seek a semblance of country living. In 1956 the nation contained about 168 million people. It is estimated that in 1975 there will be 210 million and at the end of the century 275 million.[7]

Trends in Industrial Growth

The growth in population, coupled with the present rapidly rising general prosperity, is triggering an immense expansion in the industrial complex. The people must be clothed, fed, housed, transported, and amused. Principal among the water-using industries keeping pace with this growth is that for the production of electric power. Three methods of power generation are now at hand—falling water, the burning of fossil fuels, and the release of atomic energy. No matter what the method, large quantities of water are required. Power generation in this present day, through use of fossil fuels or atomic fission or fusion, differs only in the nature of the fuel. The energy still is released to a conveying medium—steam, gaseous sodium, mercury vapor, or the like—which is used to whirl turbine rotors. The exhausted vapors are cooled to liquids, to be used again, which conversion requires great quantities of water to remove the residual heat.

The use of electric energy is growing at a fantastic rate. Studies by the Indiana Flood Control and Water Resources Commission,[7] based on data from several sources, indicates that by 1980 the capacity of all utility systems in the United States will be 380 million kilowatts and by 2000, 675 million kilowatts, as compared with 114 million kilowatts in 1955. Figure 1 shows the energy production and capacity of electric utility systems in the United States from 1920 to 1955 and estimated figures to the year 2000.

Other industries will grow in a like manner. Chemical plants requiring large quantities of water can be expected to spring up in many places. Woodpulp producing and processing industries are already beginning to utilize the hardwoods of the central states and to produce wastes which add tastes and

odors to the streams into which they are discharged. Steel mills use great quantities of water in cooling and washing their product. All of this points to an enormous increase in water requirements throughout the industrial regions of the country before the century is ended.

Trends in Irrigation in Humid Regions

Irrigation procedures in humid regions differ markedly from those in arid regions. In arid regions summer precipitation is never sufficient to grow crops and the farmer must depend upon water taken from streams whose sources are the melting snows and ground-water outflows of distant mountain watersheds or stored ground waters in the earth beneath his farm. Irrigation water requirements remain almost constant from year to year and projects are able to schedule its use on a rotation basis, so that diversions to large numbers of farms can be held practically constant throughout the season.

During nearly every summer the rainfall in humid regions is sufficient to produce crops. In some years, because of deficient or improperly distributed precipitation, crops suffer from lack of moisture and partial failures result. It is the humid region irrigator's intent to add water to his crops during protracted dry spells so as to carry them over from period of rainfall to the next. By so doing, he not only insures that a crop will mature, but by the maintenance of the moisture content in the soil at an optimum level he is able to extract a much greater yield from his fields than he would if he depended solely on the vagaries of nature to supply the soil moisture.

Since droughts usually occur at the same time over large regions, many farmers thus affected will decide to irrigate their crops simultaneously. This can only mean that the streams and possibly the ground waters from which the irrigation supplies are taken will be seriously depleted, to the detriment of other users who depend upon them, as municipalities and industries. This is the reason why serious consideration must be given to making hydrologic and water resources analyses of humid region watersheds, to insure that the water which they yield is put to the most beneficial use of those who occupy the basin.

Need for Water Resources Inventory

Whenever irrigation in humid areas is mentioned, the question inevitably arises—will there be enough water to go around? This can only be determined by a carefully-made water resources inventory of each watershed within which there is a possibility of inadequate supply.

A water resources inventory of a basin should determine these facts regarding supply: 1) the magnitude and distribution of runoff at critical sections, e.g., at the water-supply intakes to and points of return of sewage effluent from municipalities and industries within the basin; 2) the manner by which the runoff distribution could be modified by the development of water-storage sites; and 3) an evaluation of the potentialities of ground-water reservoirs as alternates or supplements to surface sources for water supply.

The inventory should determine the following facts concerning water demand: 1) present and estimated future water-supply and sewage-disposal needs of municipalities and industries now using the waters of the basin; and 2) the acreage of lands within the watershed that might economically be irrigated by withdrawal of water from surface or underground sources and water required.

Finally, this inventory should compare the supply with the demand and make recommendations as to the manner of obtaining the most efficient and beneficial use of the waters in the basin.

Water-supply inventories of different basins will produce different results. Some watersheds include large, shallow ground-water storage reservoirs which feed to the streams during periods of drought and maintain substantial low flows. Others have highly favorable reservoir sites, permitting the retention of flood flows for release during periods of drought. Some lack one or both of these advantages and may be difficult or impossible to develop as sources of water supply. Each basin will need to be developed on its own merits.

An Inventory of the Upper White River Basin, Indiana

Description

Indiana is typical of the humid region states with respect to both location and water needs. The upper White River watershed, above Martinsville in the east central portion of the State, exemplifies the type of basin for which a water-resources inventory is essential. Within this basin are situated Indianapolis, the largest city in the State, with a population of 460,000, and two important industrial centers, Muncie, population 60,000, and Anderson, population 47,000. There are four steam-electric generating stations which depend on the river for cooling water—at Noblesville (100,000 kilowatts), in Indianapolis (46,000 kilowatts), at the south edge of Indianapolis (160,000 kilowatts), and at Centerton, 30 miles downstream from Indianapolis (376,000 kilowatts).

The most critical section of the river, so far as future water requirements are concerned, is at Indianapolis. An adequate water supply for the city is now available from White River, the low flow of which is bolstered by storage releases from two reservoirs constructed on tributaries a short distance upstream by the Indianapolis Water Company. The supply of dilution water for the treated sewage effluent is not so dependable and is inadequate at times. If the city continues to grow at its present rate this will be the major water-supply problem. Lack of cooling water will also inhibit the expansion of the steam-electric generating stations, all of which now have extensive cooling-tower installations to provide for condenser cooling during periods of low river flow.

The upper White River watershed (Fig. 2), draining an area of 1,200 square miles above the Indianapolis water-supply intake and 2,485 square miles above Martinsville, is a region of low rolling hills, made up principally of the debris left by the retreat of the Illinoian and Wisconsin glaciers. The topography of the basin is such that only a few storage sites of small capacity are available.

Modification of Runoff by Surface Storage

The runoff from the White River watershed above Indianapolis can be modified but slightly by the construction of storage reservoirs. Only a few small sites are available, two of which have been developed, with a combined equivalent capacity of 0.52 inch of runoff from 1,200 square miles. Further development of reservoir sites may increase the storage capacity to one inch, but more than that now appears unlikely.

Fig. 3 shows the cumulative runoff, in inches, from the watershed during two dry periods, 1930-32 and 1952-54. Assuming an available storage of one inch, the sustained yield from the watershed above Indianapolis would be at the rate of approximately 3.9 inches per year or 350 second-feet. Under present conditions of developed storage of 0.52 inch, the rate would be 3.1 inches per year, or 280 second-feet.

Ground-water Potentialities

Sizable quantities of ground water are held in the glacial debris left as a thin mantle over the basin. This water is found at shallow depths and is easily recovered by pumping. It is replenished to a large extent from the streams during high water and discharges into them during droughts. Its removal would have some effect on stream flow.

Large quantities of ground water are also found in the underlying sedimentary rocks of ancient origin. This water is mineralized to varying degrees, in some places so much so that it is unsuited to municipal or industrial use, other than for cooling purposes.

Sufficient information is not available to determine the safe yield of the underground reservoirs of the White River watershed, but in the vicinity of Indianapolis they are not adequate to supply the city.

Water Requirements of Indianapolis and Vicinity

The City of Indianapolis requires large amounts of water for municipal use and the disposal of wastes. Three steam-electric generating stations in the vicinity need sizable amounts of river water for cooling. In Fig. 4 are shown the population of Indianapolis, its per capita water consumption, and its per capita sewage outflow from 1920 to 1955, with estimated extensions to 1980. The average daily water requirement for 1955 was 62 million gallons. The estimated requirement for 1980 is 89 million gallons. In addition to supplying the city, the Indianapolis Water Company provides raw water through a diversion canal for certain industries located within the city. The minimum measured flow is 83.7 second-feet, approximately 54 million gallons per day. This flow is returned to the river upstream from the point of discharge of the city's sewage effluent.

Indianapolis collects in its sewer system a flow about 25 percent larger than the water supply. In 1955 the sewage passing through the treatment plant averaged 75 million gallons per day. The estimated flow in 1980 is 112 million gallons per day. The minimum flow available in the White River above the point of discharge of sewage effluent from the city should not be less than the rate of sewage outflow. This degree of dilution presupposes highly efficient treatment of the sewage before release to the stream.

Relation of Water Supply to Demand

A very interesting problem arises when attempting to relate water supply to demand at Indianapolis. Two privately owned reservoirs upstream from the city are operated primarily to provide adequate flow for the city water supply. While they are capable of bolstering natural flow to a minimum of 280 second-feet at the diversion works, it is not likely that more water will be released than that required to supply the city's needs plus an amount which is sold to industries utilizing raw water.

If a minimum flow is established in the river through Indianapolis, sufficient to meet the requirements of an industrial raw-water diversion and to maintain the river, approximately 137 second-feet would be required. The following table shows the present and future water-supply needs at Indianapolis.

Table I

Relation Between Water Requirements and Supply at Indianapolis (second-feet)

Year	Water Supply		Sewage Disposal	
	Requirement	Safe Yield[a]	Outflow	River Flow
1955	93	143	117	137
1980	134	213	168	137
2000	180[b]	213	226[b]	137

a. Safe yield by operation of two reservoirs, less flow of 137 second-feet through Indianapolis, with addition of a third reservoir before 1980.

b. Estimated by exponential extension of curve of relation of time versus demand.

Future Water Use in the Upper White River Basin

The foregoing study indicates that while the water supply to Indianapolis may not become inadequate within the next forty-odd years, that available for sewage disposal will be very much inadequate. Even the maintenance of a minimum flow of 137 second-feet past the city will not provide sufficient water to at all times dilute the effluent on a one-to-one basis. Any consumptive use of water in the upper White River basin would further aggravate this condition.

Downstream from Centerton, at which point the river is last used by industry, water could be removed for irrigation without affecting users of the stream. However, any consumptive use of water from the White River would reduce the flow in the Ohio River below its mouth and the Mississippi River below the Ohio. It is granted that the amount is small, but if widespread irrigation is developed throughout the region, both the Ohio and Mississippi Rivers could be materially affected. This would further aggravate the pollution problem in the former and increase the cost of low-water navigation in the latter. In this complex civilization the use of water can have far-reaching effects.

CONCLUSIONS

Modern civilization is placing such great demands on the waters of the Nation that careful water-resources inventories are becoming essential. In many watersheds, the needs of municipalities and industries are rapidly

approaching the available supply. In such areas, consumptive use of the supply by irrigation might seriously curtail municipal and industrial growth. This is true of the upper White River basin in east-central Indiana. By careful planning and the construction of two water-supply reservoirs the city's water supply is assured for several decades. However, inadequate stream flow at the point of discharge of sewage effluent bids fair to create a biologic desert in the river for a considerable distance below Indianapolis. Also, the flow is insufficient to provide adequate condenser cooling at the three power stations at and below Indianapolis and expensive operation of cooling towers must be resorted to.

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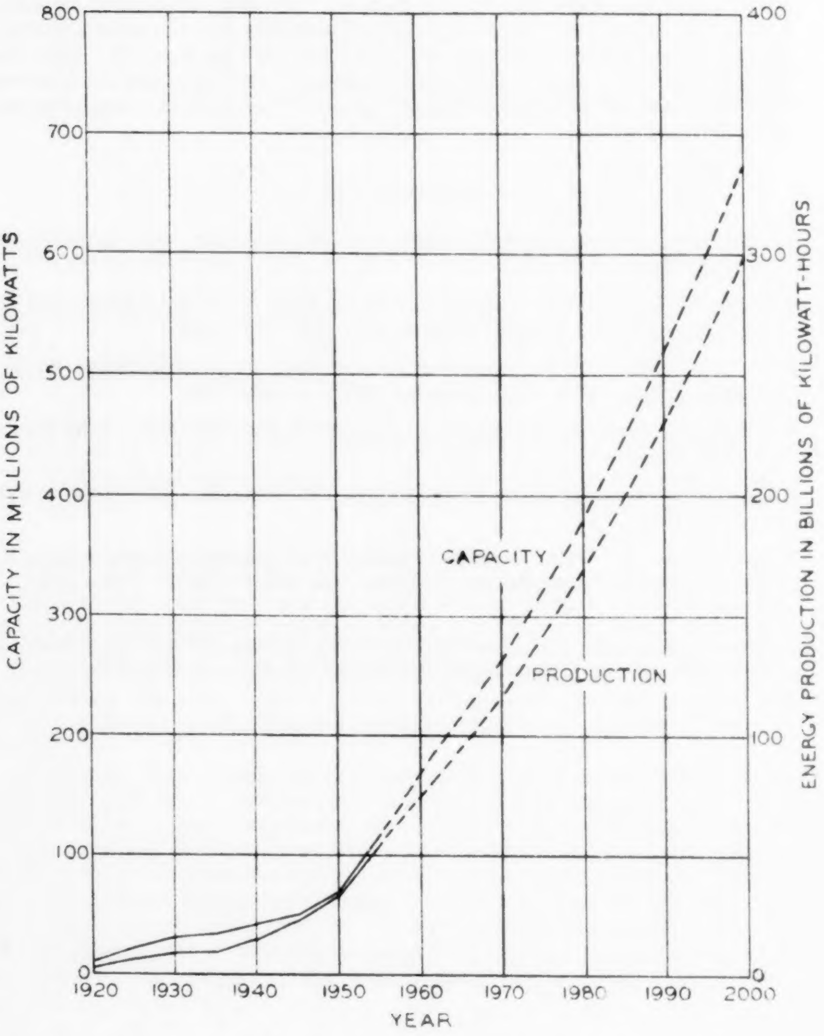
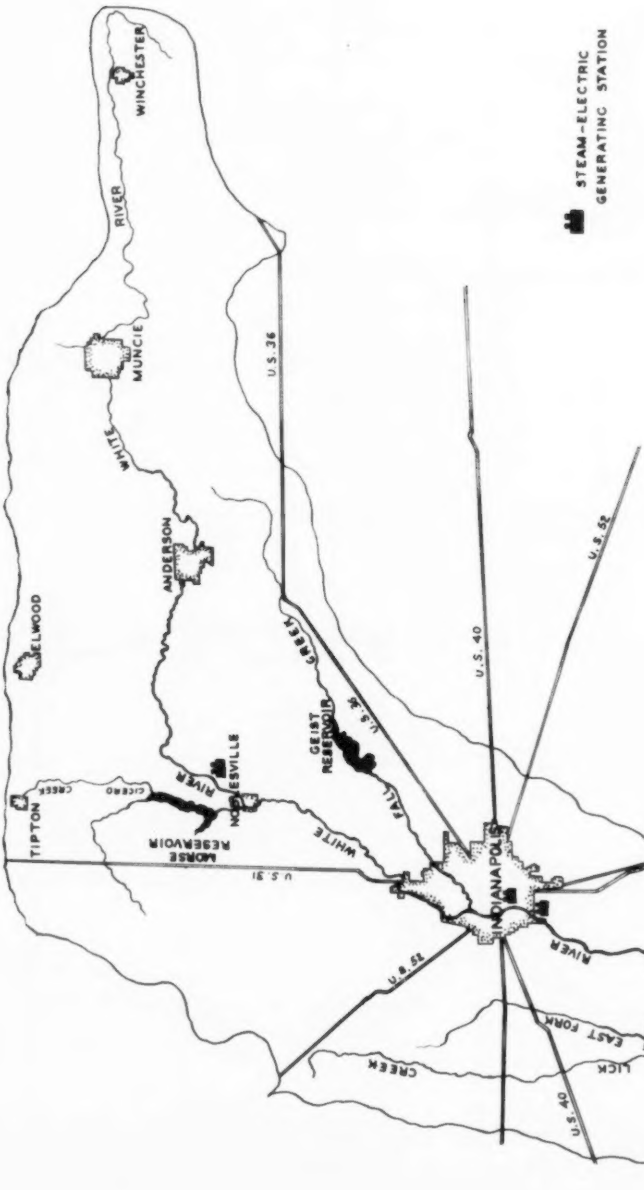


Fig. 1 Capacity and production of electric utility systems in the U. S.



UPPER WHITE RIVER BASIN
INDIANA

FIG.2

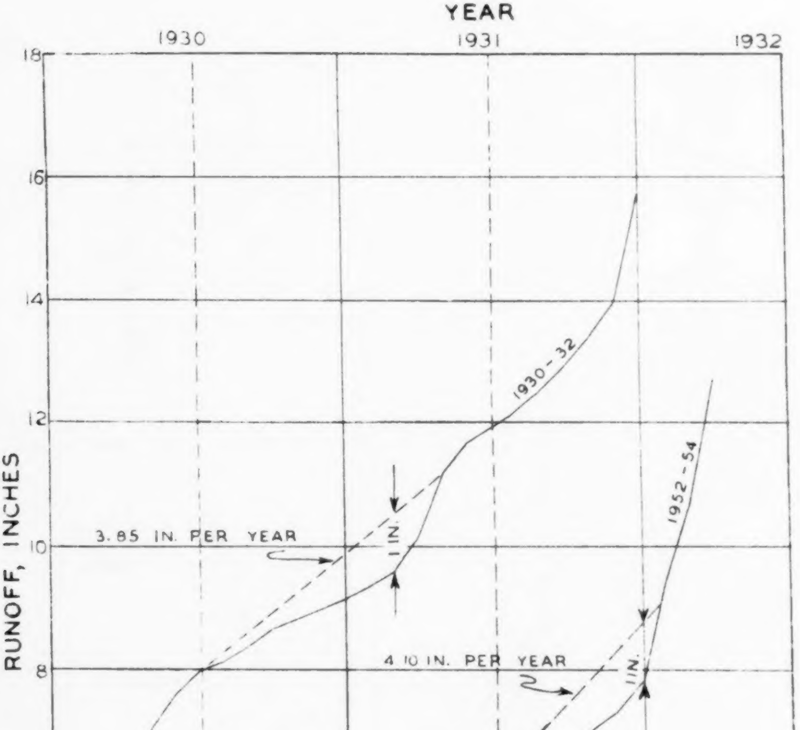


Fig. 3 Runoff and yield for one-inch storage, White River at Indianapolis

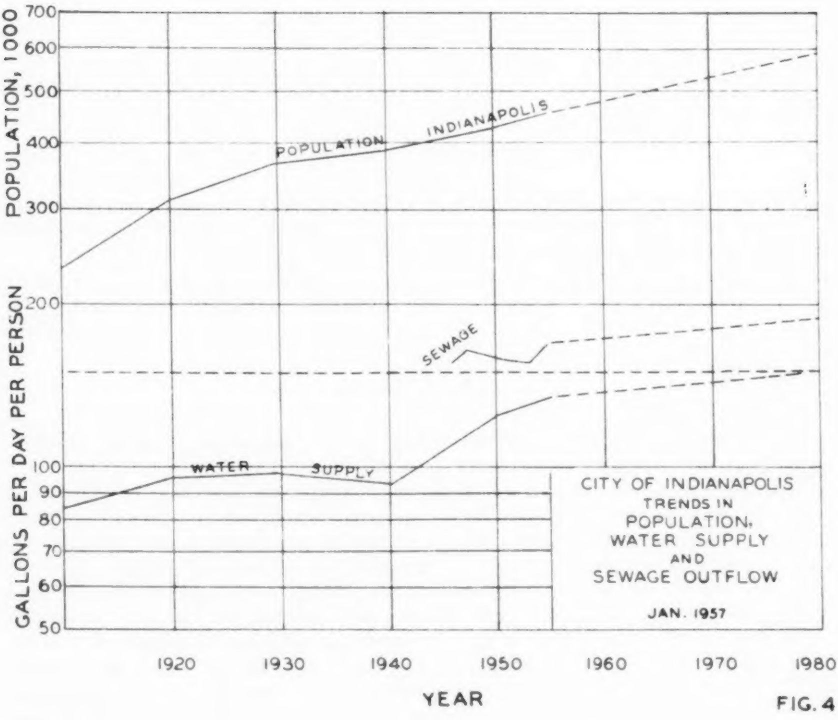

POPULATION, 1000
700
600
500
400
300
200
100
90
80
70
60
50
GALLONS PER DAY PER PERSON
POPULATION INDIANAPOLIS
SEWAGE
WATER SUPPLY
CITY OF INDIANAPOLIS
TRENDS IN
POPULATION,
WATER SUPPLY
AND
SEWAGE OUTFLOW
JAN. 1957
1920
1930
1940
1950
1960
1970
1980
YEAR

FIG. 4

Journal of the
IRRIGATION AND DRAINAGE DIVISION
Proceedings of the American Society of Civil Engineers

RESOLVING CONFLICTING DEMANDS FOR WATER[a]

Samuel B. Morris [1]
(Proc. Paper 1501)

Conflicting demands for water thrive primarily upon scarcity. In humid areas of abundance, conflicting uses may exist—in fact, do exist—but the solution and abatement are not so difficult of accomplishment, and the strains on the individual or general economy are much less. This writer is faced with a myriad of conflicting demands. Let's consider some of the types of conflict.

International Conflicts

Perhaps the most noteworthy conflicts over water are international. Throughout six thousand years of history, Egypt has built its civilization upon the waters of the Nile. But Egypt does not now have, nor never has had, full control over this historic stream, either physically or politically. Under British-Egyptian control, the Aswan Dam was constructed only in this 20th Century. While the Nile has met the need of Egyptians by its unregulated natural flow through 60 centuries, we suddenly find only 54 years after this first dam was built on the Nile that a great international struggle is triggered off by the withdrawal of financial support sought by Egypt to build a greater High Aswan Dam. Located in Egypt and proposed solely to supply irrigation, navigation and power needs to the land-hungry bulging population of Egyptians, it will at the same time create a lake extending deeply into the Sudan and spreading over irrigated lands in that new nation.

There are extensive lands in the Sudan which also could make use of the waters of the Nile. The Nile is a great international river, its waters coming from Ethiopia, through the Blue Nile, the Atbara, and the Sobat, and from the White Nile rising in the great equatorial lakes in Uganda and parts of Kenya, Tanganyika and the Belgian Congo. Already the Sudan is asserting large claims to the waters of the Nile. It has not agreed to the flooding of

Note: Discussion open until June 1, 1958. A postponement of this closing date can be obtained by writing to the ASCE Manager of Technical Publications. Paper 1501 is part of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 84, No. IR 1, January, 1958

a. Inter-Society Conference on Irrigation and Drainage, San Francisco, April 29-30, 1957.

1. Consulting Engineer, Los Angeles, Calif.

its lands by the lake which would be created by the High Aswan Dam.

And so a great water project, the proposed Greater Aswan Dam on the historic international Nile River in one of the world's oldest countries, Egypt, may be the springboard for another international crisis.

Closer to home, we all are familiar with the long conflict between Mexico and the States of California and Texas over waters of the Colorado River and the Rio Grande. About the turn of the century, the predecessors of the Imperial Irrigation District found the most feasible route to divert water from the Colorado River onto their Imperial Valley lands in California was by means of an old watercourse that left the river and passed through Mexico before entering California. For the right to bring water through such a route, Mexico demanded fifty percent of the water diverted from the river. This was agreed to, but, during periods of low flow on the Colorado and unsettled political conditions south of the border, Imperial Valley lands were unable to secure their full fifty percent of the inadequate low flows.

This international difficulty over the inadequacy of the low flow of the Colorado to meet irrigation requirements, the continual threat of floods, and municipal water and power needs, finally enabled California interests to secure passage of the Boulder Canyon Project Act of 1928, which provided for the construction of Hoover Dam and power plant and the All-American Canal. One of the provisions of this Act was that none of the benefits of storage should go to any foreign nation.

However, the continued conflict over the waters of the Colorado and the Rio Grande, neither of which river discharge is adequate to meet the full water requirements of all available lands north and south of the border, led to the compromise international agreement in 1944. Under this agreement the United States guaranteed to Mexico from the Colorado River 1,500,000 acre-feet annually, released to meet the varying demands of agriculture. This release is double the maximum Mexican use before the regulation afforded by Lake Mead above Hoover Dam. The compromise was justified as being in the interest of international amity.

At the same time, conflicting claims to the waters of the Rio Grande were determined. Left to the future are possible conflicts over the quality of water from the Colorado River available to Mexico, the user farthest downstream, after all upstream diversions for use and returns to the river have had their slow and insidious effect.

In contrast to these evidences of international conflict over use of water in arid and semi-arid regions, is the record of the historic Danube, rising in southwest Germany and Switzerland and flowing through Austria, Hungary, Yugoslavia, along the border between Romania and Bulgaria and between Romania and the Soviet Union, to the Black Sea. On this great international river of commerce and major historic cities, there has never been an international crisis over conflicting claims to the flow of the Danube. There have been conflicting claims to its navigation and commerce from feudal times but no conflicts over diversions from the river. All have used it freely for their water supply, waste disposal and navigation.

The sharp contrast between the long history of the Danube and of the Nile emphasizes the essential difference in conflict over the waters of these great international waterways—the one in the humid area free from conflicts over diversion and use of its waters and the other in an arid area where increasing conflict is indicated as it becomes increasingly apparent that the Nile has

insufficient flow fully to provide for all of the several nations' demands for its use. This use is mainly for irrigation. Irrigation—that consumptive use of water so necessary to sustain life in an arid area—and yet so limited and precious to the people and their lands. The situation on the Colorado River and the Rio Grande parallel those of the arid lands of the Nile.

One of the conflicting demands for water is for the opportunity of hydroelectric development. The great dams and power plants on the main stem of the Columbia River are dependent on streamflow originating in major part in British Columbia and, also for substantial streamflow regulation afforded by the Arrow Lakes in the headwaters of the Columbia River in Canada. Until recently, there has been consideration only that there should be adequate water storage. Now a new problem has arisen.

Spurred on by the success of diverting water from the Skeena River to a shorter course and large fall into the Kitamat enabling the Aluminum Company of Canada ultimately to develop 2,000,000 kilowatts close to seaboard, the Canadians are now proposing to divert the Columbia River in Canada into the Frazer River. By this means they could develop the river's full head to tidewater in Canada instead of losing 1300 feet of the head to projects on the Columbia River in the United States.

This is an international problem which shall have to be solved by negotiations and agreements between the two nations in a combination of law and international amity between friendly nations.

Interstate Conflicts

Here at home the Ohio-Mississippi or the Hudson rivers may be likened to the Danube. There is no conflict over the diversion and use of the waters of these rivers except for the conflict over Great Lakes water levels and Chicago's diversions of Lake Michigan water into the Illinois River for navigation and sanitation. This controversy has been decided by the U. S. Supreme Court Decision limiting such diversion to 12,000 cubic feet per second. On the Ohio River there are some conflicts involving discharge of sewage and industrial wastes. An interstate board has been appointed to maintain the sanitary quality of this river. Another problem in the summer is that of the overheating of the Ohio River through repetitive use of the river for cooling purposes by steam-electric plant condensers. But these problems on the rivers in humid areas can be solved without too much difficulty.

On the other hand, there is serious conflict between the several States over the diversion and use of the waters of the Colorado River. The principal consumptive use is for irrigation purposes. The Colorado, like the Nile, is a river flowing from areas of large rainfall in its distant headwaters, through semi-arid areas, and finally through arid dry desert areas on its path to the sea. As previously mentioned, there was for many years international conflict over use of its waters. Again, like the Nile, the first major consumptive use of the Colorado River has been to irrigate the desert valleys along the River, at Palo Verde, Imperial Valley, and in Mexico.

Oddly, the shortage of water on the Colorado is being brought about not by the conflicting works of local persons, corporations or public agencies, but by the indulgences of the great paternal Government of the United States, which is causing water to be put on high lands of short growing season at costs many times what the irrigator can afford to pay, or would pay if it were not for federal subsidy and assistance.

In the case of the Colorado River, it may well be, as has been stated by an eminent engineer, that there is sufficient water in the river for all domestic, industrial, municipal and irrigation use in the United States that can afford to fully carry the high costs of bringing its water to the place of use. And so, if this be true, some may say the cause of the major conflict in use and threatened shortage rests on the United States Government itself.

My own strong opinion is that greater population and industry will grow in the states of the Colorado River if the waters of the river are left to a more free economy which would result in these precious waters remaining available for gradual development for the higher use of population and industry. The Upper Basin of the Colorado River includes the largest deposits of energy in the United States. These are coal, oil, gas, and uranium deposits. Someday they should support great industries in the Rocky Mountain region. Such industries and growing populations will create increasing demands for water that may encroach upon the water theretofor used by agriculture.

Conflicts Between Municipal and Irrigation Uses

Everywhere it is realized that domestic and municipal uses are the highest use of water. The States generally provide that such use shall be superior to all others. It should be recognized that municipal use is that combination of domestic and industrial use which together form the water requirements of a city or of a metropolitan area. If the lands first irrigated are the same lands absorbed by expanding urban requirements, a natural and happy condition results in the normal conversion of farm lands to the higher value of urban use. This has most notably taken place in metropolitan Los Angeles, including Orange County, and is becoming an increasing factor in the metropolitan areas in Sacramento, Alameda, San Mateo, Santa Clara and San Diego Counties.

A far different and unhappy condition arises when it becomes necessary for an expanding city to purchase the lands and water rights from an existing or contemplated irrigation area such as was done by the City of Los Angeles in 1905. The then city of 200,000 people voted bonds to purchase lands and rights to divert the waters of Owens River. This water was brought 240 miles in order that the city could grow to 2,000,000 or ten times its then population. Los Angeles finally expended more than $36,000,000 to purchase lands, town lots, residential and business improvements in Owens Valley and Mono Basin in order to protect this diversion of 320,000 acre-feet per annum from these areas, including pumping from groundwater storage.

The generation of people from whom these lands and rights were purchased 30 to 50 years ago has largely passed and there is a larger new population and more prosperity in the valley than ever before, thanks to recreational use and expenditures. Yet we all know the tremendous political pressures that continue to be generated in these Mountain Valleys at the expense of the City of Los Angeles. And, let the record be kept straight—Los Angeles did not condemn a single parcel of land or water. All purchases were made in the open market by paying the seller his asking price. Also water has been continued to meet the needs of the several towns in the valley, and some 30,000 acres are irrigated when water is available in excess of the capacity of the aqueduct to Los Angeles.

Accordingly, I cannot too strongly urge against any planned temporary use

of water for irrigation which contemplates that at some future date a distant city shall acquire such irrigated lands and dry them up to transfer the water for the increasing demands of population and industry on such distant lands.

Conflict Between Other Uses of Water

Even in humid areas, with more than adequate water for all consumptive use purposes, there are conflicts between water users, sometimes between one character of use and a different character of use or, competition between users for the same character of use. Those who use our rivers for waste disposal are frequently in conflict with fish and wild life, recreational uses and with domestic and municipal uses. Higher requirement of purification of wastes adds to the cost of waste disposal, betters the stream for other uses, and may decrease the cost of water treatment for cities downstream. If the treatment of wastes is adequate, use of the river by fish and wild life and for recreational uses is preserved at the proper expense of the industries and cities contributing these wastes to the river.

Reservoirs to provide for flood control, stream regulation, water supply or power development take land out of other beneficial uses and alter fish and wild life habitats. This latter is sometimes beneficial, but not always so. Anadromous fish cannot pass high dams, this causing major problems to large commercial fisheries as well as sportsmen. The fish problems of the Columbia River are a good example. There are problems in the drainage of swamp lands. New values in land uses may be created and at the same time game refuges may be destroyed.

Provision of empty storage space for flood control is inherently in conflict with use of such capacity for storage of water for water supply, irrigation or power development. It is necessary to add the several storage requirements for beneficial purposes to determine whether there may be sufficient storage created to fill the requirements of each beneficial use. If not, then some beneficial use must be decreased or, perhaps, foregone altogether.

Planning Against Development of Conflicting Uses

Coming to the affirmative side, what can be done to avoid any conflict in uses of a water resource? Certainly this can best be approached through intelligent planning of each drainage basin on a multiple-purpose use basis. This can only be done safely if adequate basic data are available.

Water requirements are inseparably linked to the optimum land use by present and reasonably to be foreseen populations. This requires topographic, geologic, and soil classification mapping as well as long-time rainfall, runoff, sedimentation, temperature, humidity, and evaporation records and studies. Upon this base of physical data, we must project the type of people who are to inhabit the area, their customs and economic opportunities in order reasonably to predict the best ultimate water and land development.

Such a study will reveal certain favorable sites and methods of water storage and diversion, types of dams and reservoirs, opportunities for hydroelectric development, if any; the best balance of securing most economical flood control, by combination of storage, channel protection, flood plane zoning, and flood forecasting. Flood damage insurance is a new element to be

taken into consideration in determining the most economic flood control program. Such a survey and study will likely determine that certain natural dam and reservoir sites must be protected, and reserved from other use in order later to be utilized to accomplish the most economic water development for all useful purposes.

If the area involved is in a semi-arid region, where the natural waters are insufficient to supply all needs, then it is necessary to look as far ahead as possible in order to determine what lands can be best irrigated without robbing the higher economic opportunity of domestic and municipal use. Particularly, it is most helpful, as previously noted, if the lands to be irrigated are the same ones which may later be the locale of expanded urban use.

Long-time Problems

The best concept of long-time problems to be faced by men and nations is revealed by the study of geology, hydrology and archeology, and the realization that the forces of nature continue to exert themselves. Our individual time on this planet is but an instant in the long geologic history of the Earth. Even the period of a million years since man first emerged is short in geologic time. The forces of nature in uplift of mountains, depression of valleys and slippage along faults in the earth's crust are continuing. Along the San Andreas fault it is about two inches per year, a mile in 31,680 years or a half mile since the last glacial period. The mountains and hills are being eroded and their rocks and soils deposited in the valleys and the finer silts carried into lakes or the sea. In this process, the courses of streams and rivers change as their beds are built up and they break through their banks to occupy lower lands on the debris cones near the mountains or lower lands in the valleys. By such processes, great fertile valleys such as the Sacramento-San Joaquin or the Mississippi Valley are created.

Erosion and deposition, those great sculptors of nature, will always continue. Most of the acts of man tend to increase their rate through deforestation and cultivation of the soil. The effects may be lessened by development of better forestation and land management methods. At our best, we can hardly approach the lower rates of erosion by water and wind, which have continued through geologic times. The river systems also carry man's wastes to the sea, but in volume man-made wastes other than his effect on erosion do not compare with nature's ever wasting of rock and soil into the rivers and thence to lakes or the sea.

Thus, through the passing of time, will all our great dams and reservoirs be silted up. Some future generation may ponder the wisdom of those who constructed the dams and raised them until all possible water storages have been filled and, area by area, man becomes dependent upon the natural flow of the rivers. This time of dependence on unregulated streamflow will come sooner to the semi-arid regions of full development than to those of the humid areas. This results from the characteristic nature of the occasional heavy rainfall causing the muddy runoff into streams and rivers. Also there is the effect of the greater dependence upon water storage to meet the seasonal demands of irrigation. As there is no deterioration or depreciation of unused irrigable lands or unused reservoirs, it would appear sound public policy not to develop irrigation or storage until their use is required.

Our records of rainfall and runoff are pitifully short, scarcely over 100

years. All our forecasts are based upon such short-time records with the assumption that there is no change in long-time climatic factors. When we look back 6,000 years to the beginning of civilization and irrigation along the Nile, the Tigris and Euphrates, we are looking back nearly half the time since the last ice age. It is only reasonable to believe that the climate, rainfall and runoff at the time of the beginnings of irrigation were far different from those of today. We may still be slowly receding from the great rainfall associated with the ice age, or there may be much longer wet and dry cycles than we have found or experienced.

In the pressure for immediate short-time weather forecasts to meet the needs of aircraft, ships at sea, and man's day-to-day activities, the study and research of long-time departures from normal of climatic factors, particularly rainfall, runoff and temperature, have not been progressed sufficiently. While all water uses are involved in the uncertainty of future climate, the irrigator and all agriculture are the ones most seriously affected. This is increasingly true in areas of low rainfall approaching semi-arid and arid conditions.

Such climate changes will affect the irrigator in two ways. Increased drought will require increase in irrigation water to produce additional foodstuffs and fibers, while, on the other hand, increase in rainfall will produce larger regional crops but will require less water for irrigation and less production from irrigated agriculture. This will become increasingly true as supplemental irrigation spreads more and more into the humid areas and is generally accepted as the means of making more certain the production of staple food crops in all years, rather than dependence upon nature providing proper rainfall distribution.

In the humid East, we can expect competition for water between increasing supplemental irrigation and the expanding needs of domestic and industrial water supply. The water requirements for supplemental irrigation will vary in cycles of wet and dry years. The demands for municipal use will continue to advance. In all municipal water supply sufficient water for today means shortage for tomorrow unless additional water supplies are available and works to utilize them have theretofor been constructed. In these combinations of events, conflict over available water is bound to arise in the humid areas where so little attention has been given to development or administration of water rights.

Ground Water

In general the discussion up to this point has referred primarily to surface water but is generally true for ground water supplies, or combined surface and ground water supplies. Long-time life of ground water supplies are affected in additional ways. Many are being drawn upon at rates greater than their safe yield. Unless other water supplies are available, the economic life of such ground water supplies is limited. This limit, however, is different for each use, depending upon the capacity of the water user to pay. The domestic and industrial water user can afford a cost of water several times that to the irrigator. Accordingly, if a common overdrawn ground water supply is furnishing both urban and irrigation use, it is but a matter of time until one by one the farmers are forced to abandon their irrigation unless they have a prior right to sufficient water to meet their requirements or additional water can be imported.

There are other factors which may contribute to the failure of a ground water supply. These relate to water quality. The use and re-use of water for irrigation, or the discharge of wastes from municipal and industrial use may finally make the water unfit for use. Here again the irrigator is the first to suffer as municipal and industrial users can afford water treatment methods beyond those available to the irrigator.

It is fundamentally clear that for permanence of irrigation, substantial quantities of water in excess of the combined rainfall and net irrigation crop requirements must be applied to the lands. It is also equally clear, in the case of a closed ground water basin, that there must be provision for extraction of ground water and conveying it beyond the basin limits or ultimately the ground water will become saline as are the natural surface lakes in a closed basin. During the degradation of such ground water, the irrigator will be the first to suffer as he can least afford to pay the cost of water treatment.

SUMMARY

Conflicting demands for water can best be met by advance planning for all uses on a drainage basin basis. This may involve consideration of the whole gamut of water uses, domestic, industrial, municipal, irrigation, drainage, hydro-electric power, waste disposal, flood control, navigation, recreation, fish and wild life. If water supplies cannot be provided sufficient to meet every future requirement, then it is necessary to determine whether additional water supplies can be imported from afar. Sometimes such importation becomes feasible at a later date, after population and values are adequate to finance the cost of an imported water supply. If sufficient water for all purposes cannot be obtained then decision should be made on economic grounds as to which uses shall be restricted or not be provided for.

In arid and semi-arid parts of the world, especially, it is vitally important to determine the best type of economy to keep within the limits of water supply. With domestic and municipal use everywhere accepted as the highest use, irrigated agriculture must be designed to fit into the ultimate water-land economy. If the same lands first used for agriculture will gradually become urbanized, there may be little difficulty in the absorption of irrigated lands by urban requirements. If water must be taken from irrigated lands for later urban use elsewhere and the former irrigated farms dried up, then a tremendously difficult political-social-economic problem is created. Every effort should be made to avoid such a situation. From the standpoint of inferior economic value and less ability to pay, it would appear that the role of irrigation inevitably is subordinate to domestic and municipal water supply. In case of conflict with such higher use, irrigation is bound to lose to domestic and municipal use unless in the unforseeable future population food requirements may require the utmost use of land for food production.

Paper 1502 January, 1958 IR 1

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IMPORTANCE OF PHREATOPHYTES IN WATER SUPPLY[a]

C. B. Thompson,[1] M. ASCE
(Proc. Paper 1502)

ABSTRACT

Importance of Phreatophytes in Water Supply, by C. B. Thompson. (IR) Salt cedar (tamarisk) is the dominant type of 80 different species of phreatophytes that infest 17,000,000 acres of land and waste 25,000,000 acre-feet of water in the western United States. This illustrated paper describes its occurrence and spread over 440,000 acres in New Mexico. Water use and methods of eradication and control are also discussed.

INTRODUCTION

The word phreatophyte is derived from two Greek words meaning well and plant, thus a phreatophyte is a well plant. The term covers a broad classification of vegetation which is considered to be water-loving, i.e., plants which habitually obtain their water supply from the zone of saturation or from the overlying capillary fringe. Phreatophytes are generally considered as a group of plants which do more harm than good and are known to be high users of water. Examples are: tamarisk (salt cedar), cottonwood, willow, baccharis, mesquite, and arrow weed. The species of tamarisk most commonly found in this country is Tamarix pentandra.

In the western United States about 80 different species of phreatophytes have been identified. These plants which cover approximately 17 million acres in the West deplete the ground-water reservoir by an estimated 25 million acre-feet annually.

Since 1900 the growth of salt cedar in the United States has been phenomenal. This has resulted in the gradual replacement of infestations of other

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a. Presented at Intersociety Conference on Irrigation and Drainage, San Francisco, California, April 29-30, 1957.

1. Chief, Technical Division State Engineer Office, Santa Fe, New Mexico.

phreatophytes with almost pure salt cedar in many drainage systems throughout the Southwest.

Salt cedar is believed to have been introduced into this country from the area surrounding the Mediterranean Sea by the Conquistadores and early settlers. It has been reported to have been growing for centuries in the Jordan River Valley of Palestine.

The salt cedar plant has a bushy structure and spreads out close to the ground. All species in this country with the exception of the evergreen athel, Tamarix aphylla Karst, are deciduous with minute frond-like leaves. The physiology of the salt cedar is such that it is very tolerant to both saline and alkali soils, grows rapidly when subjected to a high water table and a warm climate, and will survive long periods of inundation of root crowns. On the other hand it will also withstand extreme drought conditions and can survive comparatively severe winters. It has been identified in India at elevations of 11,000 feet. An indication of its tendency to seek ground water is evidenced by the fact that plants growing along the Suez Canal have been found with roots which penetrated to the water table at depths exceeding 90 feet. All of the deciduous types of salt cedar are prolific seed producers, one small plant having been estimated to produce in excess of 600,000 seeds during a single season. They may also reproduce by means of cuttings and from root stock. It is interesting to note that the manna of Biblical times which sustained the Israelites in the desert is now believed to be an edible secretion of the tamarisk tree Tamarix mannifera. When this tree is attacked by a certain species of plant louse, a white substance oozes out, crystallizes, and drops to the ground where the Israelites found it.

Only scant mention was made of the salt cedar plant in the flora of this country until about the middle of the 19th century. In 1856 tamarisk stock was listed in seed and nursery catalogs in various states, especially in California. The sale of the plants by this means for ornamental use in parks and gardens undoubtedly accelerated the spread to widely scattered parts of the country. The earliest specimen collected in the field in the United States was found in the Fairmount Park area of Philadelphia in 1877. Other specimens were collected along the ocean near Corpus Christi and Galveston, Tex. in 1894.

It was not until 1909 that salt cedar was observed growing along natural stream channels. Thus, the escape of this plant from cultivation heralded the advent of almost unbelievable infestation, whereby it invaded nearly every major stream system in the Southwest. Plants are now adapting themselves and are thriving in Colorado, Wyoming, North Dakota, throughout the South, and in the New England states.

From the first reported infestation in New Mexico, near Mesilla Park in 1910, salt cedar has increased to an area of approximately 113,500 acres in the lower valleys of the Rio Grande and Pecos River. Other large and as yet unmapped areas of salt cedar can be seen in the San Juan, Gila, and Canadian River drainage basins. Figure 1 shows how this phreatophyte has spread through the stream systems of the State as well as in some of the closed basins.

Recent estimates indicate that phreatophytes of all types infest a total area of 440,000 acres in New Mexico, and waste 869,000 acre-feet of water annually.

The Phreatophyte Subcommittee of the Pacific Southwest Inter-Agency Committee is at present compiling a map which will show the infested areas for the entire western United States.

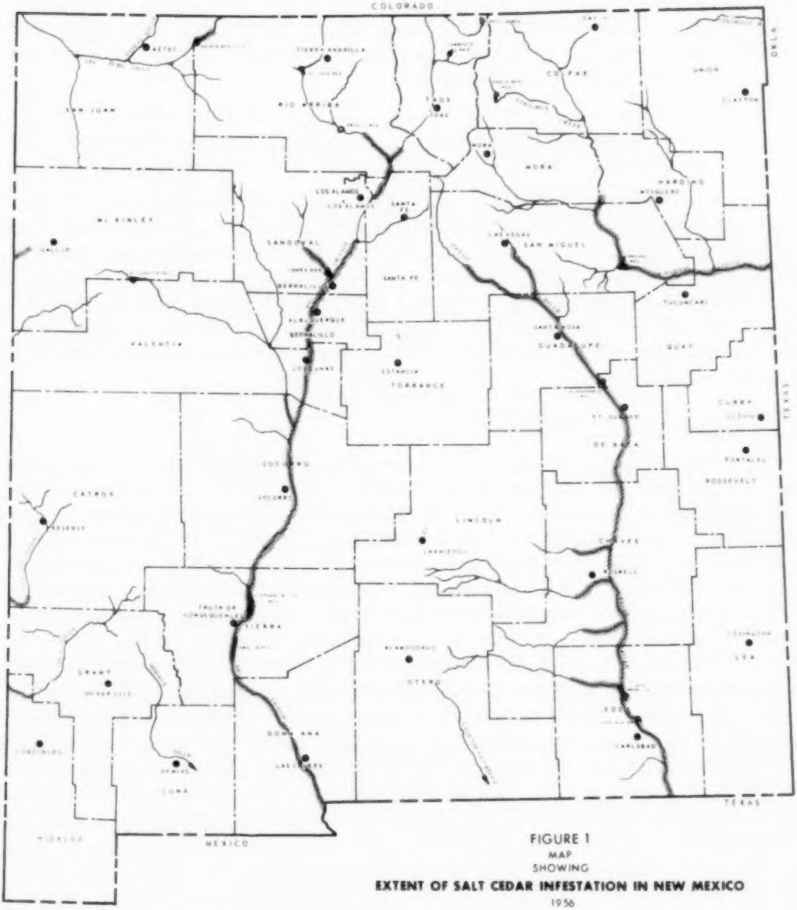


FIGURE 1
MAP
SHOWING
EXTENT OF SALT CEDAR INFESTATION IN NEW MEXICO
1956

HATCHING INDICATES INFESTED AREAS

Water Use

The rate of consumption of water by phreatophytes varies widely with plant species and with local conditions. For a given species the principal governing factors are: (1) depth to water table, (2) climatic conditions, and (3) density of growth. Water use is maximum when the water table is shallow, the climate hot and arid, and the growth dense.

Following is a resume of studies of water use by phreatophytes.

Safford Valley Investigation

Probably the most intensive and one of the first comprehensive studies on the consumptive use of water by phreatophytes was made by the U. S.

Geological Survey in cooperation with the Phelps-Dodge Corporation during 1943 and 1944. This work was accomplished in the Gila River Valley near Safford, Ariz., and was under the direct supervision of J. S. Gatewood, Project Engineer. At that time the following methods of determining water use by bottomland vegetation were applied:

1. Tank
2. Transpiration-well
3. Seepage-run
4. Inflow-outflow
5. Chloride-increase
6. Slope-seepage

Three of these methods were developed during the investigation and had not been used previously. The results of each of the six methods were found to be within 20 percent of the average. For the 12-month period of study it was determined that water use for the several phreatophytes in the area was as follows: 7.2 feet for salt cedar, 4.7 feet for baccharis, 6.0 feet for cottonwood, and 3.3 feet for mesquite. The volume-density method of evaluating variations in the density of water-loving vegetation was also developed during this investigation.

Blaney Studies

Work by Harry F. Blaney of the Agricultural Research Service, an authority who has spent some 38 years in the study of consumptive use of phreatophytes and hydrophytes, indicates that in 1940 at Carlsbad, N. M., tamarisk used 4.8 feet of water per year with a 3-foot water table. Another study carried on at San Luis Rey, Calif., showed that cottonwood with 3- and 4-foot water tables used on an average of 7.6 and 5.2 feet, respectively. Correlations have been made by Blaney and others between observed evaporation data and consumptive use. For example, in relating the consumptive use of tules to pan evaporation, it was found that at Los Griegos, N. M., consumptive use was 83 percent of pan evaporation; at Victorville, Calif., 95 percent; and at San Luis Rey, Calif., 94 percent. Some empirical formulas have been developed by Blaney and Morin for computing evaporation and consumptive use when temperature and humidity data are available. Since actual measurements of consumptive use for large areas are time consuming and expensive, these formulas are valuable in that they offer a rapid method of estimating water use by phreatophytes without a detailed investigation.

Draper Survey

The Bureau of Reclamation, under the supervision of E. L. Draper, conducted an investigation on phreatophytes in the Middle Rio Grande Valley in the reach from San Marcial to Bernardo, N. M., in 1947. The method of computing consumptive use in this survey was an extension of the Safford Valley Investigation (tank method), modified for differences in temperature, precipitation, and other factors. Figure 2 is a graph which shows how the average annual consumptive use of several species of phreatophytes varies with the depth of water table. The graph also shows the consumptive use of other nonbeneficial plants and the water loss from bare ground as well.

The curves in Figure 2 were developed by averaging consumptive use rates for the following locations in the Middle Rio Grande Valley: Cochiti, Albuquerque, Belen, Socorro, and Bosque del Apache. Extreme salt cedar values are for Socorro, with a maximum of 10.8 feet per year with a 2-foot depth to water table, and a minimum of 2.6 feet per year at Cochiti with an 8-foot depth to water table.

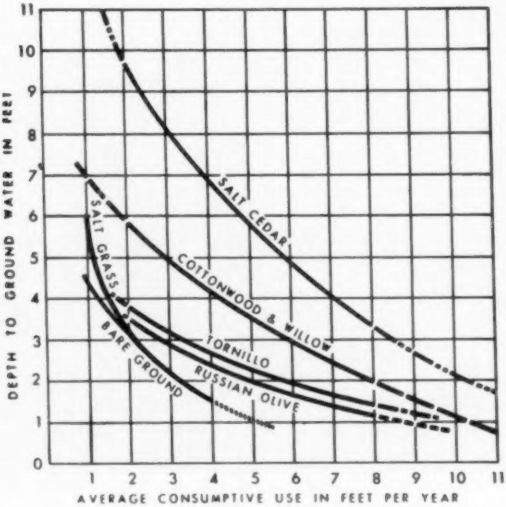


FIGURE 2

CONSUMPTIVE USE OF NONBENEFICIAL VEGETATION
vs
WATER TABLE DEPTH
MIDDLE RIO GRANDE VALLEY

Decker Transpiration Measuring Apparatus

An apparatus for measuring the transpiration of phreatophytes has been developed by Dr. John P. Decker of the U. S. Forest Service at Arizona State College, Tempe, Ariz. In the laboratory a single leaf, twig, or an entire plant is sealed in an illuminated, constant-temperature glass chamber that is ventilated at a known rate with dry air. The absolute humidity of the air flowing out of the chamber is recorded continuously by an infrared gas analyzer, and this can be related directly to the transpiration rate. It is understood that Dr. Decker is now in the process of adapting his equipment for use in the field. Undoubtedly, this apparatus will be useful in determining the amount of water used by phreatophytes and other plants.

Problem Areas in New Mexico

For many years salt cedar growth in the State was confined largely to the lower valleys of the Rio Grande and the Pecos River, with especially heavy infestations in the delta areas of Elephant Butte and McMillan Reservoirs. Recently, however, it has spread into the watersheds of the San Juan, Canadian, and Gila Rivers.

Rio Grande Basin

The most important problem area in this basin is located in the reach between Bernardo Bridge and San Marcial. Figure 3 is an aerial photograph

Fig. 3. Extensive Salt Cedar Infestation in Delta Area of Elephant Butte Reservoir.

showing an extensive salt cedar infestation in the delta area of Elephant Butte Reservoir.

A Bureau of Reclamation report by H. R. McDonald and W. M. Borland indicates that between 1947 and 1955 the volume-density of salt cedar in the reach from Bernardo to San Marcial increased by more than 3,000 acres in equivalent area, or by slightly more than 50% of the 1947 density. Total estimated areal coverage in that area in 1955 was 52,000 acres.

An explanation of the volume-density method of vegetative surveys may be helpful. This method was developed in the Safford Valley of Arizona and, briefly is as follows: areal density is the ratio of area covered by all plants to the total ground area, vertical density is the ratio of the vertical depth of fronds on a plant to the maximum possible depth on the species, and volume-density is the product of the areal and vertical densities. The volume-density of a species varies with latitude. For instance, a stand of salt cedar in Sonora, Mexico, might be 25 feet in height and have a volume-density of 100% while a corresponding stand in Wyoming with a 100% volume-density might be only 12 feet high, the difference being due to climatic factors.

Equivalent area is an area of 100% volume-density which would contain the same volume of frondage as the area in question.

Figure 4 portrays graphically the increase in infested acreage and volume-density in a reach of the Middle Rio Grande Valley from San Marcial to Bernardo for the period 1914 to 1955.

Using the volume-density survey method it was determined that there is an equivalent area of approximately 13,420 acres of salt cedar in this reach of the river. It has been calculated, with an average water table depth of 4 feet and a net consumptive use of 5.8 feet, that annual water use attributed directly to salt cedar in this reach would be 77,800 acre-feet.

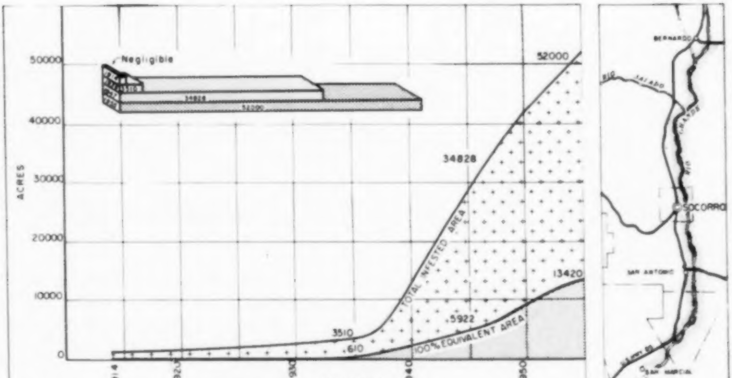


FIGURE 4

INCREASE OF SALT CEDAR AREA, RIO GRANDE VALLEY, BERNARDO TO SAN MARCIAL, N. M.

Another area which is readily becoming infested is located between Elephant Butte and Caballo Dams. A major portion of this growth, approximately 9,000 acres, is in the delta area of Caballo Reservoir. Using an average water table depth of 6 feet, an equivalent area of 1,550 acres, and a net consumptive use of 4.3 feet, the annual consumptive use of salt cedar in this reach is estimated to be 6,670 acre-feet.

Pecos River Basin

The salt cedar problem in the Pecos River Valley is quite similar to that in the Rio Grande. An infestation of approximately 600 acres, which was reported in the McMillan Delta in 1915, has now spread throughout the valley from Alamogordo Dam to the New Mexico-Texas state line and covers an area of approximately 42,500 acres, or an equivalent area of 20,200 acres.

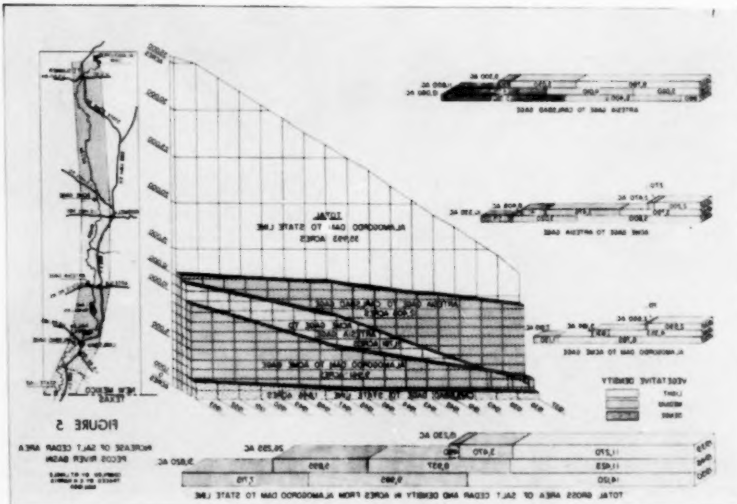
Figure 5 illustrates graphically the rather phenomenal growth of salt cedar in four reaches of the Pecos River in the period from 1937 to 1953.

Based on a consumptive use of 5.8 feet and an equivalent area of 20,200 acres, the water use of salt cedar in this area is estimated to be 117,000 acre-feet annually.

Other Basins

Salt cedar has been identified growing in the San Juan River Basin as indicated on Figure 1. While this growth is causing no particular concern at present, it is believed that with the construction of the Navajo Dam and other units of the Upper Colorado River Storage Project the seriousness of this problem will be greatly intensified.

In the Gila River Basin salt cedar has been reported in the vicinity of Redrock, N. M. This development has apparently taken place within the last few years and as yet does not constitute a serious problem. However, downstream in the vicinity of Safford, Ariz., and in the delta of Coolidge Reservoir, infestations are already of considerable concern to the San Carlos Irrigation District.



Dense growths have been observed below Conchas Dam on the Canadian River and are also developing upstream from the reservoir. These growths will undoubtedly spread to the canals and drains of the Tucumcari Project, causing a sizeable increase in operation and maintenance costs for the Arch Hurley Conservancy District.

Recently thin stands of salt cedar have been observed in the Estancia Valley and Tularosa Closed Basins. Undoubtedly careful field inspection would now reveal salt cedar growing in practically every watershed in New Mexico.

Control Measures

Several measures have been used in an effort to eradicate and control the growth of salt cedar. Five of the more important methods, which will be discussed separately, are as follows: aerial and ground spraying with herbicides; clearing, discing, and mowing; burning; channelization and drainage; and flooding.

Spraying with Herbicides

Trials to control salt cedar by the application of herbicides were first started in May 1948 by personnel of the Dow Chemical Company on a 5-acre plot south of Avondale, Ariz.

Since that time, extensive experimental work and large-scale spraying has been done by numerous State and Federal agencies as follows: Bureau of Reclamation and U. S. Dept. of Agriculture using 6.5-acre plots near Dome, Ariz., 1948; Bureau of Reclamation on a 100-acre tract in McMillan delta, N. M., 1948-49; Imperial Irrigation District along irrigation canals in

Southern California, 1948-49; Bureau of Reclamation and U. S. Dept. of Agriculture on 10-acre plots near Yuma, Ariz., 1949-51; Bureau of Reclamation on 2,630 acres in McMillan delta, N. M., 1951; Bureau of Reclamation and U. S. Dept. of Agriculture on 74 one-third-acre test plots near Phoenix, Ariz., 1951-55; Bureau of Reclamation and N. M. State Engineer on 30,000 acres in Socorro Div. of Middle Rio Grande Conservancy Dist., N. M., 1951-54; Bureau of Reclamation on 1,800 acres in Caballo Reservoir, N. M., 1951-56; Bureau of Reclamation and Agricultural Research Service on 30-acre tract near Gillespie Dam, Ariz., 1956; Arch Hurley Conservancy Dist., N. M., along irrigation canals (by helicotper) 1956; Bureau of Reclamation and Ft. Hays State College on an area in vicinity of Cedar Bluff Reservoir in Kansas, 1956; and Bureau of Reclamation and Agricultural Research Service in an area along Fivemile Creek, a tributary of the Bighorn River above Boysen Reservoir in central Wyoming, 1956.

Formulations of low volatile esters as well as amine and sodium salts of 2,4-D and 2,4,5-T are the chemicals which have been most widely used in salt cedar control work. Experience, however, indicates that the most effective of these is a mixture of esters of 2,4-D and 2,4,5-T applied at rates exceeding 2 pounds per acre. Diesel oil and oil-water emulsions have been used as carriers. Effectiveness of kill has varied in different localities from only a few percent on old plants to 100 percent on seedlings.

The application of herbicides by airplanes is the most economical method for the treatment of extensive infestations and was used in a majority of the cases cited above. Figure 6 is a photograph of a Piper Cub completing a spray run in the San Marcial Area of the Middle Rio Grande Valley in New Mexico.

The aerial spray method, however, has been found unsuitable for use near agricultural areas. In 1955 landowners in the San Antonio area of the Middle

Fig. 6. Plane Completing Spray Run in San Marcial Area Middle Rio Grande Valley.

Fig. 7. Bureau of Reclamation Ground-Spray Rig with 100-Foot Boom.

Rio Grande Project were awarded $25,000 from the Western Flying Service for alleged damages to cotton crops.

Ground-spray rigs, to a large degree, overcome the drift experienced by aerial spray equipment and are therefore recommended for use in areas where cotton fields are in close proximity to infestations. Figure 7 is a photograph showing a ground-spray rig with a 100-foot boom which has been built by the Bureau of Reclamation for use in the Middle Rio Grande Valley. The unit has a 1,750 gallon tank and can spray an area of approximately 40 acres in one hour.

Spraying costs vary according to the method and rate of application, type and concentration of herbicide used, formulation of carrier, etc. Using 17 contracts, covering some 37,000 acres, as a basis, costs for aerial spraying ranged from $2.36 to $15.38 per acre with an average of $5.32. Spraying with ground rigs has not as yet been accomplished on a large scale; consequently, comparable cost data are not available. Costs for the treatment of canal banks with ground rigs average about $20.00 per mile on the Middle Rio Grande Project.

Clearing, Discing, and Mowing

Due to damage suits arising from alleged injury to cotton crops by spraying with herbicides, clearing of salt cedar by mechanical means has been considered by some as a satisfactory and desirable method of control.

During 1954-55, the New Mexico State Engineer Office in cooperation with the Bureau of Reclamation cleared and disced 4,741 acres in the San Marcial area of the Rio Grande Valley at a cost of $11.19 per acre. Rental equipment used consisted of D-8 Caterpillar tractors with dozer blades, and Towner discs. During 1955-56, equipment was purchased and an additional 7,665

Fig. 8. D-8 Tractor and 20-Foot Towner Disc.

acres were cleared and disced. This work was accomplished at a cost of \$3.02 per acre not including depreciation on the equipment. Figure 8 is a photograph of a D-8 tractor pulling a 20-foot Towner disc.

Figure 9 is a map showing the work area of the cooperative State Engineer-Bureau of Reclamation clearing program.

Experience of the International Boundary and Water Commission in the El Paso area indicates that floodways can be kept free of salt cedar growth by periodic mowing with rotary brush cutters pulled by ordinary farm tractors. The cost of this treatment averages \$7.82 per acre for two cuttings per year. The U. S. Fish and Wildlife Service has also used this method with some success in the Bosque del Apache National Wildlife Refuge. Costs reported in this area average \$3.03 per acre for a single cutting.

Burning

The burning of salt cedar growth without cutting has been tried in numerous localities but in practically every case the practice has proved to be unsatisfactory. The canes in an upright position seem to be rather fire resistant and in most cases are sufficiently separated so as not to support combustion.

Burning can be successfully accomplished as an aftermath of dozer clearing operations provided that the material is properly raked and stacked in windrows. Before firing, sufficient time should elapse to permit adequate drying. The selection of a windy day for burning operations and the use of kerosene or used crank case oil will be found advantageous.

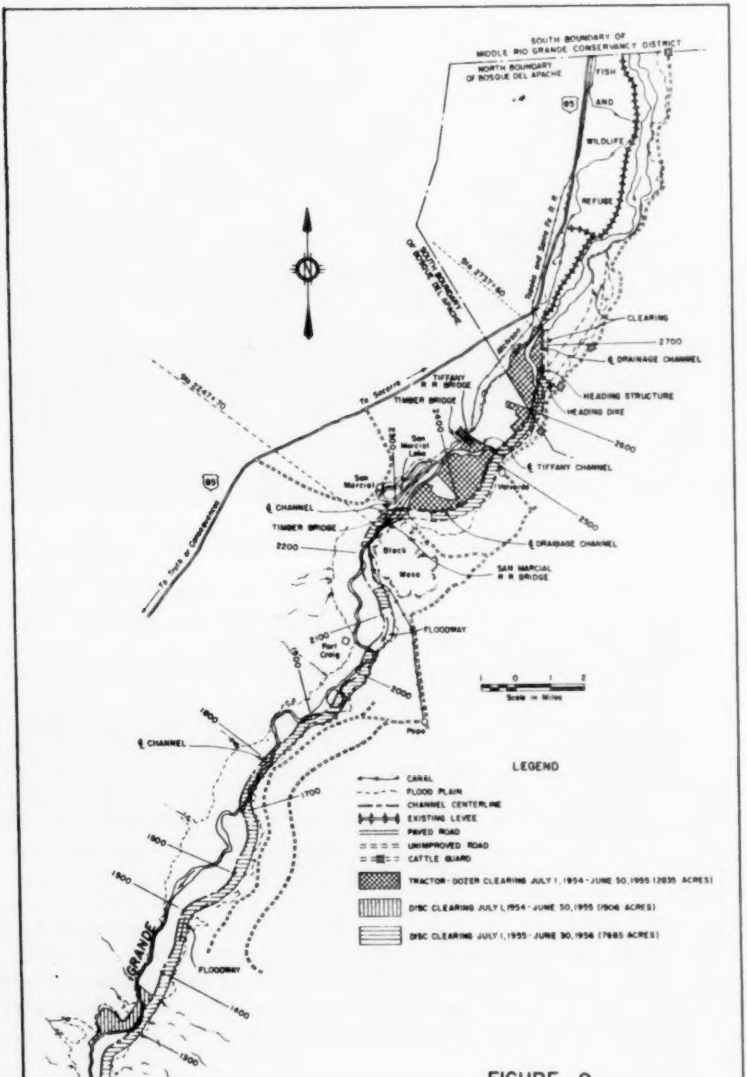


FIGURE 9

U.S. BUREAU OF RECLAMATION
AND
STATE ENGINEER OFFICE
COOPERATIVE SALT CEDAR CONTROL PROGRAM

COMPILED FROM U.S. BUREAU OF RECLAMATION DATA
DRAWN BY J. J. FOX
AUGUST 1956

Channelization and Drainage

As indicated in Figure 2, the consumptive use of salt cedar and phreatophytes varies with the depth of the water table, i.e., annual use with an 8-foot water table might be 2.6 feet while with a 2-foot water table it could be as high as 10.8 feet. The recognition of this fact has formed the basis for channelization and drainage as a means of water salvage by reduction of evapotranspiration losses.

The first large-scale water salvage program to be undertaken by the Bureau of Reclamation in the West was started in 1951 in the Rio Grande Valley upstream from Elephant Butte Reservoir. The work was begun by the construction of 7.7 miles of pilot channels through a large swampy area located in the vicinity of San Marcial. Operations were accomplished on a force account basis by the State Engineer Office at a cost of $72,000.

Bureau of Reclamation contracts, totaling $2,752,000, covered construction of a low-flow channel and a cleared floodway, 31 miles in length, varying in width from 1,000 to 1,400 feet. Material removed in the construction of the low-flow channel was placed on the river side to form a spoil bank levee parallel to the new channel. A 50-foot brush fringe was left on the floodway side of this levee as a protective measure against erosion. Graveled access roads along each side of the channel provide a means for patrol and maintenance. The low-flow channel has a capacity of 2,000 c.f.s., and will carry the entire flow of the river about 80% of the time. Discharges exceeding the capacity of the low-flow channel are directed down the floodway. The low-flow channel averages 10 feet in depth, has 2:1 side slopes, and a 30-foot bottom. Velocities in the channel average about 4 feet per second, thus permitting the conveyance of most of the sediment. Figure 10 is an aerial view showing the completed lowflow channel and floodway.

Fig. 10. Aerial View of Completed Low-Flow Channel and Floodway, Middle Rio Grande Project.

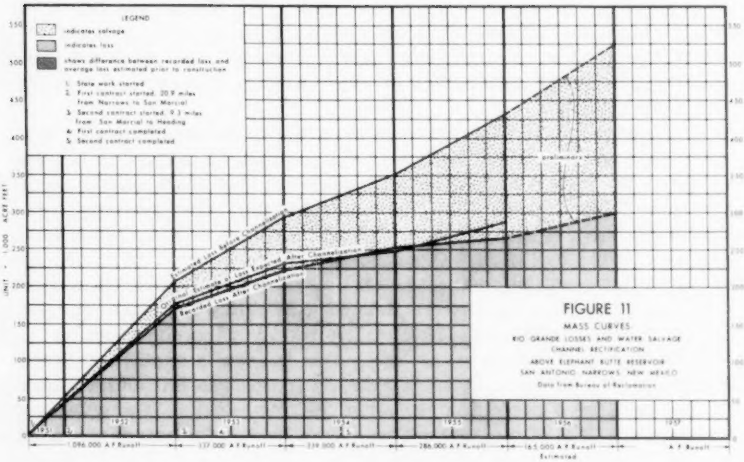


FIGURE 11
MASS CURVES
RIO GRANDE LOSSES AND WATER SALVAGE
CHANNEL RECTIFICATION
ABOVE ELEPHANT BUTTE RESERVOIR
SAN ANTONIO NARROWS, NEW MEXICO
Data from Bureau of Reclamation

Figure 11 shows graphically the increase in water salvage as channelization in various reaches of the river was completed during the period from 1951 to 1954. The overall water salvage resulting from this work is estimated to be 45,000 acre-feet per year.

The low-flow channel and floodway are currently being extended upstream from the present heading for a distance of approximately 40 miles. This extension will cost in the neighborhood of $3,900,000 and will result in the salvage of an estimated additional 40,000 acre-feet of water annually.

Similar work, on a smaller scale, has been accomplished on the Pecos River in New Mexico. In 1948 and 1949 a 4.2-mile canal of about 1,200 c.f.s. capacity was constructed between Kaiser Lake and McMillan Reservoir to salvage water spreading out in swamps and meandering channels. The partial draining of Kaiser Lake and the drying up of adjacent swamps has undoubtedly salvaged a substantial amount of water. The success of this work and of the channelization program in the Rio Grande has led to the Pecos River Commission proposal of a similar program in the delta area of McMillan Reservoir. This $2,700,000 Bureau of Reclamation project, now under consideration by the Congress of the United States, advocates the construction of a low-flow conveyance channel of 1,500 c.f.s. capacity, a floodway levee, and a cleared floodway of 40,000 c.f.s. capacity, extending about 16 miles upstream through the delta area. It is estimated that construction of the proposed works would result in the annual salvage of approximately 24,490 acre-feet of water which is now being lost to salt cedars and other phreatophytes.

Flooding

It is known that the complete inundation of salt cedar infested areas is an effective means of eradication. However, the use of this method is rather limited since it can only be applied in reservoirs which can be filled completely whenever necessary and in canals with check gates which will permit considerable variation in the water level.

During the period from 1940 to 1949 this method was successfully used in the Caballo Reservoir in New Mexico; however, during the prolonged drought of the last eight years the infestation has reached such proportions that other means of control may become necessary.

CONCLUSIONS

Evidence available at this time indicates that salt cedar is rapidly becoming the predominant nonbeneficial vegetation in the lower river valleys of the Southwest where high water table and climatic conditions are ideal for its growth. It is further evident that this plant is becoming established in the higher tributaries and is invading some of the stream systems of the Northwest. It is therefore believed that, due to its extremely high water consumption and the fact that it constitutes one of the major operation and maintenance problems on irrigation and flood control projects throughout the western states, Congressional legislation should be enacted and funds appropriated for a Federal program. It is further concluded that:

1. At present channelization is the most effective means of salvaging water in the river channels and reservoir delta areas in the heavily silt-laden river basins of the West.
2. Significant amounts of water may be salvaged by the eradication of salt cedar and other phreatophytes.
3. A method of eradicating salt cedar must be found which is more effective and economical than those currently in use.
4. Finding a commercial use for salt cedar would afford a quick method of control.
5. Additional and more conclusive studies should be carried on to determine the consumptive use of phreatophytes.
6. The volume-density method of vegetative surveys should be adopted as a standard by all state and Federal agencies.

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FACTORS AFFECTING THE USEFUL LIFE OF RESERVOIRS[a]

Carl B. Brown,[1] M. ASCE
(Proc. Paper 1503)

ABSTRACT

The useful life of reservoirs includes (1) length of life and (2) service value. Controlling factors in reservoir silting are shown to be the capacity-inflow ratio and sediment content of inflow which is governed by watershed characteristics. Flexibility in design and site conservation through proper project formulation is urged.

It has been common practice in the engineering profession to think of "the useful life of reservoirs" only in terms of length of life. This concept probably stems from the familiar business practice of depreciation in which a facility is assumed to wear out or become obsolete in some given period of years. But if one were talking about the useful life of citizen John Doe he would connote not so much his length of life as what he accomplished during that life. It is not inappropriate to view reservoirs also in this light. Thus, the useful life of a reservoir may be considered from two points of view, namely, (1) factors that affect its length of life, and (2) factors that affect its service value or usefulness.

Factors That Affect the Length of Life

Most modern reservoir dams of substantial size are engineered to have a practically unlimited life so far as the structure itself is concerned, providing it is given reasonable maintenance. Modern geologic techniques for dam site

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a. Paper presented at the Intersociety Conference on Irrigation and Drainage, San Francisco, Calif., April 29, 1957.

1. Director, Planning Division, Soil Conservation Service, U. S. Dept. of Agri., Washington, D. C.

exploration and engineering skill in structural design assure against all but the remotest chance of foundation failure or earthquake destruction. Present-day knowledge of maximum runoff potentials has led to spillway designs and other features of construction that leave only the slimmest chance of failure from flood flows. Even in remote parts of the world where actual hydrologic data are largely lacking, the safety of large dams is almost completely assured by the large margin of safety built into the structures. Of course, enormous additional costs are often essential to provide "factors of safety" that will compensate for the lack of adequate hydrologic data.

Needed Flexibility in Design

On the other hand, the design of every reservoir project should be, and in many cases must be, governed by economic considerations. The expected benefits must exceed the costs. Some segments of the engineering profession, however, seem to have acquired an inflexibility of thinking about the design of dams. By virtue of rigid insistence on the application of uniformly high standards of design to all dams regardless of size, purpose served, or losses that would be sustained by the remote possibility of dam failure, many worthwhile smaller projects have been found economically unfeasible. Let us be absolutely clear on this point. It is universally agreed that major dams, such as Hoover dam or Grand Coulee dam, must be designed, so far as humanly possible, to eliminate even the remotest chance of failure.

The highest possible standards of design should be applied to dams whose failure would create heavy and widespread losses of human life and property. On the other hand, many dams useful for irrigation or other purposes which impound only a few hundred or a few thousand acre feet of water can be located at sites where remote chances of overtopping by flood flows might be tolerated in design. For example, there is no record that modern, properly compacted and well-sodded earth fill dams with excavated spillways in natural earth or rock have failed suddenly. Research studies have shown that well-vegetated earth dam and spillway surfaces have high resistance to the scouring action of velocities up to 6 or 7 feet per second with depths of flow of 3 or 4 feet.

The probable gradual failure of such dams under greater velocities would usually produce hydrographs in valleys below them that become broad crested within short distances. If no significant concentrations of population, industry, or other high property values exist within reasonable distances below such sites, lower design standards may be fully justified in order to obtain the economic benefits of water storage.

Reservoir Silting

An eminent English Geologist of the early 19th Century, Sir Charles Lyell, is credited with saying: "The history of a lake is the history of its death." In more recent times, the late Professor Rollin D. Salisbury of the University of Chicago wrote in his textbook on "Physiography": "Rivers are the mortal enemies of lakes." Both of these authorities had observed that geologically as well as in historic times a lake begins to fill with sediment from the moment it is formed. A reservoir is, of course, merely an artificial lake. All reservoirs are gradually dying from loss of their capacity caused by

deposition of sediment, most of which is transported into them by inflowing streams.

Most dams because they are being constructed to last almost indefinitely will become largely useless from silting long before the dams themselves reach a stage of significant deterioration. The problem of essential concern is the rate at which the capacity loss will occur, and what practical steps, if any, can be taken to lessen the rate or effects of reservoir silting.

Impact of Silting on Reservoir Development

Reservoir silting may have both a short range and a long range impact. The short range impact includes the effect of silting on the economics of project development. Under some conditions the rate of silting in a given reservoir may be so rapid that the value of its services is insufficient over even a short period of years to amortize the cost of the development. For this reason alone the probable rate of silting needs to be forecast with some accuracy as a part of any economically sound project development.

The long range impact is implicit in the fact that dam sites, especially for larger reservoirs, are a severely limited resource—much more so than our reserves of oil, iron ore, and other non-renewable natural resources. Once exhausted by reason of being filled with sediment, these reservoir basins are for all practicable purposes gone forever. At least no economically feasible method of reclaiming most reservoir sites is known at this time. Thus, even if silting is not so severe as to jeopardize the amortization of a reservoir in the short run, nations must be concerned with all practicable means of conserving their dam site resources for the long run.

Literature on Reservoir Sedimentation

It would be impractical here to attempt to outline all facets of the subject of reservoir silting and methods for its control. Fortunately, the voluminous English-language literature on the subject is well documented and annotated through 1954 in accessible bibliographies published under the auspices of the United States Government's Federal Inter-Agency Committee on Water Resources.[2]

Factors Influencing the Rate of Silting in Irrigation Reservoirs

This Conference is primarily concerned with water for permanent irrigation agriculture. Therefore, it seems appropriate to confine this discussion to reservoirs in which water storage for irrigation is an important purpose.

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There are two dominant factors controlling the rate of silting in any storage reservoir. They are: (1) the relation of capacity to inflow, and (2) the content of sediment in the inflow. Other factors that modify the long-term loss of storage capacity include: (1) the trap efficiency of the reservoir (that is, what proportion of the incoming sediment is deposited), (2) the character of the sediment which affects the volume of capacity lost for any given sediment percentage by weight in the inflow, and (3) the method of reservoir operation which together with character of the sediment affects the percentage of sediment deposited below and above the limits of useful storage that can be withdrawn from the reservoir through controlled outlets. Basically, however, these three latter factors are modifiers and do not usually have a major effect as compared with the capacity-inflow ratio and the average sediment content of the inflow.

These two principal factors have a complete range of interplay, that is, a reservoir having a small capacity-inflow ratio and a small sediment content in the inflow might have the same average percentage loss of annual capacity as a reservoir having a large capacity-inflow ratio and a large sediment content in inflow. For example, the Tongue River reservoir in Montana has a ratio of 0.23 acre-feet of capacity per acre-foot of annual inflow and a sediment accumulation rate of 0.19 acre-feet per square mile of drainage area. Elephant Butte reservoir on the Rio Grande has a capacity-inflow ratio of 2.0, nearly ten times as much, and a sediment accumulation rate of 0.52, nearly three times as much, but the capacity loss in Tongue River reservoir has been 0.45 percent annually and in Elephant Butte reservoir 0.51 percent or nearly the same.

Obviously the highest rates of silting would occur with small capacity-inflow ratio and high sediment content up to the point where much of the sediment was passing the dam in released flow or through the spillway. It has been reservoirs with such a characteristic that have shown very high rates of silting. An example is Lake Waco on the Bosque River, Texas, which had a capacity-inflow ratio of 0.2, and a sediment accumulation of 0.59 acre-feet per square mile annually. Its capacity depletion has been 2.5 percent annually.

On the other hand, reservoirs with high capacity-inflow ratios and low sediment content will have the least rates of silting. For example, Fort Supply reservoir in Oklahoma has a capacity-inflow ratio of 1.7, a sediment accumulation rate of 0.11 acre-feet per square mile, and an annual capacity loss of only 0.17 percent.

With a given sediment content in the inflow, reservoirs providing only seasonal storage will have higher annual losses of capacity than reservoirs designed to provide hold-over storage for two or three years. Conversely, with a given capacity-inflow ratio, the annual loss of capacity will be directly proportional to the sediment content of the inflow except as modified in a minor way in most reservoirs by trap efficiency, character of sediment, and similar factors.

Sediment Yield of Watersheds

The sediment content of inflow is the product of many inter-related factors, among the most significant of which are (1) the source and character of runoff, (2) susceptibility of soils and valley alluvium to erosion, (3) the hydraulic

efficiency of the drainage system, and (4) the areal extent and density of vegetative cover on the watershed. The last of these four is in most watersheds the controlling factor. As a consequence, despite heavy precipitation, steep slopes, erosive soils, and efficient channels, the sediment content of most larger streams in the northern tier of western states of the United States is comparatively low. The primary reason, of course, is that most of watersheds are reasonably well protected by forests and grass. Under such conditions, even reservoirs which provide only seasonal storage in this region have generally low rates of annual capacity loss.

At the opposite extreme are the arid southwestern states, where native vegetation at most is sparse, and the semi-arid dry farming areas where soils are exposed to erosion a large part of the time. Under such conditions even hold-over reservoirs having capacities twice the average annual flow and ten times the minimum annual flow may have moderate to high silting rates. Truly high rates, however, especially those exceeding one-half to one percent capacity depletion annually are largely confined to reservoirs providing only seasonal storage in the naturally barren, or semi-barren, cultivated, or severely overgrazed watersheds where annual precipitation is something less than 20 inches. Major western reservoirs having silting rates in excess of 0.5 percent annually include: Elephant Butte reservoir, New Mexico, 0.52%; Great Salt Plains, Oklahoma, 0.60% ; John Martin, Colorado, 0.61%; Altus reservoir, Oklahoma, 0.68%; Lake Dallas, Texas, 0.72%; Black Canyon reservoir, Idaho, 0.89%; Possum Kingdom reservoir, Texas, 1.02%; Lake Nasworthy, Texas, 1.26%; Alamogordo reservoir, New Mexico, 2.30%; and Lake Waco, Texas, 2.49%.

From the short run point of view, the impact of silting on the economic justification or cost amortization of reservoir storage is largely confined to projects providing (1) only seasonal storage generally less than the minimum annual inflow, and (2) having watersheds that are characterized by sparse vegetation, extensive cultivation, or severe overgrazing. Where such a combination exists, planning engineers should make a thorough study of the potential silting problem.

Data and techniques are now adequate in most areas to permit reasonably reliable predictions of probable long-term silting rates. As an example, an investigation was made in 1945-46 of the probable rates of silting in reservoirs proposed to be constructed in the Sacramento-San Joaquin drainage basin in California.[3] Prediction of silting rates was based on surveys of 24 then existing reservoirs of various sizes in the basin with a reconnaissance survey and classification of erosion conditions in their watersheds and those of the proposed reservoirs.

Subsequently, seven of the reservoirs for which predictions were made have been constructed by the United States Army, Corps of Engineers. Following the major basin-wide flood of December 1955, the Sacramento District, Corps of Engineers, made sedimentation surveys of these reservoirs, which at the time of survey were 2-1/2 to 8 years old. The total accumulated sediment measured in the seven reservoirs was approximately 2,250 acre-feet.

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3. Brown, C. B., and Thorp, E. M. Reservoir sedimentation in the Sacramento-San Joaquin drainage basins, California. U. S. Soil Conservation Service, Special Report 10, 69 pp., illus., processed. Washington, D. C., July 1947.

Projection of the annual silting rates estimated in the 1945-46 SCS study to these seven reservoirs gives an estimated sediment accumulation of 2,290 acre-feet. Such close concordance in totals is, of course, fortuitous, because survey results on individual reservoirs compared with the prior estimates showed plus and minus variations of 30 to 50 percent for the three reservoirs in which appreciable sedimentation had occurred. For the short-term periods involved, however, which included one exceptional storm, the validity of the technique used is considered to be adequately confirmed for the purpose of determining whether sedimentation would be a significant factor in project justification or reservoir design.

Control of Reservoir Silting

From the long run standpoint, national interests are best served by considering all feasible means of conserving the capacity of all available reservoir sites.

Methods used throughout the world for the control of reservoir silting are described in a publication of the Department of Agriculture.[4] Methods studied included settling basins, vegetative screens, off-channel locations, by-pass canals, venting density currents, dredging, draining and flushing, flood sluicing, and others. The conclusion reached was none of these methods has more than limited and special purpose application because of generally unfavorable site conditions, limited physical effectiveness or economic infeasibility. Only two methods offer substantial prospects.

Watershed Protection

One is watershed protection. This is basically the use of watershed lands within their capability for use without deterioration and treatment with measures required to protect the land against erosion. The effectiveness of erosion control methods in reducing the sediment content of runoff has been demonstrated in many small watersheds, although not yet have needed measures been installed widely enough on large watersheds to give an adequate quantitative test of their net effectiveness on major rivers. This point is being rapidly approached on some watersheds, however, such as that of the Washita River in Oklahoma.

Site Conservation Through Project Formulation

The second method of achieving the conservation of our reservoir sites against ultimate loss by silting comes in project formulation and reservoir design. Within the limits justified by project economics, the capacity-inflow ratio should be increased to the point where for any given site condition the predicted silting rate should certainly be less than 0.5 percent annually and preferably less than 0.25 percent. Furthermore, consideration should be given to any peculiar site conditions or use requirements that might make

4. Brown, C. B. The Control of Reservoir Silting. U. S. Dept. Agri., Misc. Pub. 521. 166 pp., illus. Washington, U. S. Gov't. Print. Office, 1943. Revised August 1944.

feasible such special methods of silting control as, for example, locating the storage basin off channel and feeding it by diversion or installing sluices.

This brings us back to the first concept presented, namely, that the useful life of a reservoir is not merely how many years it will serve, but also what service value or usefulness it will have during its life span. This must be determined in one way or another as a premise for project formulation. One of the more important considerations in project formulation should be that the history of a reservoir is the history of its death from silting—no matter how long nor how short this may be. If this axiom is accepted, the corollary in project formulation becomes: Is this the best way and the best time to utilize this exhaustible and non-renewable natural resource? Or would the nation be better served by utilizing this site for another purpose or need now or reserving it for more pressing needs for this or other purposes at a later date? Such questions involve the highest considerations of statesmanship. They should not be passed over lightly.

The principle of reserving a part of our natural resources for generations yet unborn became a part of the national policy of the United States as far back as 1892 when the first national forest reserves were set aside from the national domain. The principle was greatly extended and solidified under the administration of President Theodore Roosevelt. During this era the policy of managing the national forests to serve the "greatest good of the greatest number in the long run" became so firmly established that it has not been successfully challenged in the last 50 years, despite many attempts to do so. Currently it appears that public awareness and acceptance will keep it safe for many years ahead.

Unfortunately in the United States we have not always been so careful in husbanding or protecting our irreplaceable dam sites. Examples could readily be cited of major irrigation reservoirs completed in the last 10 years where either the quality of water or the quality of land or both are so poor that permanent irrigation agriculture in the area is most improbable. Other examples could be cited where with good water and good soil the crops produced are dominantly those already in surplus supply and hence are going into government storage or disposal channels. These same crops may be urgently needed 20 years from now to support our rapidly growing population. But in the meantime the reservoirs that will grow them have been dying during periods of surplus.

Pertinent also but not always given the consideration it deserves is the question of whether, in the long run, storage at a given site will best serve for irrigation, or for municipal and industrial water supply, or for power or for some other purpose. Too often the concept of the benefit-cost ratio based on returns from different purposes projected from existing relations of one purpose to another has been the sole or dominant consideration in project formulation.

Policy Considerations Affecting the Useful Life of Reservoirs

Some of the questions that need to be given more thoughtful study prior to initiating the death of a reservoir site are these:

(1) In the light of future atomic and solar power potentials how much more reservoir capacity should be devoted to hydro-power storage?

(2) In those watersheds where increased agricultural production can be achieved cheaply and quickly by conserving water where it falls, or in upstream watersheds, should this form of water use be fully developed before large reservoirs are planned for storage of the residual runoff for irrigation use at relatively high cost far downstream with the consequential channel and evaporation losses resulting therefrom?

(3) In areas where climate, mineral resources, or transportation facilities point inevitably to substantial increases in domestic and industrial water use, should reservoir sites begin their death cycle now for other purposes such as irrigation?

(4) Where climate and soil permit the growth of specialty crops such as citrus needed in a balanced national diet, should needed irrigation storage be diverted to industrial uses that could be developed elsewhere?

(5) Should there be a world-wide inventory of remaining major and intermediate size reservoir site resources and, after appropriate classification, national plans for the timing of their development by private enterprise and by local and national governments in accord with the principle of conserving site resources to serve the greatest good of the greatest number in the long run?

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INFLUENCE OF CLIMATE ON IRRIGATION AGRICULTURE[1]

Wayne D. Criddle[2]
(Proc. Paper 1504)

ABSTRACT

Climate is the major factor that determines the kind of crops that can be grown in an area, and whether or not irrigation is necessary. Where growing seasons and temperatures are favorable to agriculture, rainfall is the important element in determining irrigation water requirement. Growing season rainfall may limit the amount of irrigation water needed, but it also may create many problems that do not exist where summer rainfall is minor or nonexistent.

Over the ages, man has congregated where water is available for quenching his thirst and that of his animals, and for raising the crops needed to satisfy his needs for food and fiber. Without water, neither animal nor plant life can long exist. However, although water can be a blessing if available as needed, it can also become a curse when not controlled. The 1955 floods in the great Sacramento Valley of California are testimony to its great destructive power. Over the years terrible losses of life and property are reported because water is uncontrolled.

In 1887, the Hoang-Ho River in China flooded and 900,000 people perished. Two years later, the Johnston, Pennsylvania, flood occurred with 2,200 people losing their lives. In 1952, the Missouri, Mississippi and Red Rivers went on a rampage. As a result of modern rescue equipment and organization, only 3 lives were lost but 100,000 were made homeless and 2,500,000 acres of land were flooded. Flood control works are taming many "would be floods" such

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1. Paper prepared for Intersociety Conference on Irrigation and Drainage, April 29 and 30, 1957, San Francisco, Calif.
2. Irrig. Engr., Agri. Research Service, U. S. Dept. of Agriculture, Utah State Agri. College, Logan, Utah.

as the 1957 runoff in the Tennessee Valley which was one of the largest of record but which few people heard about because it did little damage.

With all the advancement made in this atomic age, man still cannot control the elements. Nature still varies the amount of precipitation that falls and how it falls. There are wet years and dry years, periods of drouth and periods of excess precipitation. Sometimes these periods are of several years duration. The severe drouth that is now occurring in Southern Arizona and New Mexico began more than 10 years ago. During such periods, water users must be able to draw on large carry-over reservoirs that have been filled during the wet years if they are to meet their requirements.

The early settlement and development of agriculture in the United States was in the eastern half of the country where annual precipitation is generally in excess of 30 inches and fairly well distributed throughout the year. Complete crop failures, because of drouth, just don't happen in this area. However, yields often are greatly reduced because of lack of moisture at the right times. A few enterprising farmers along the Atlantic Coast states found out more than a century ago that applying a little extra water during the hottest and driest part of the year assured better yields than was possible without irrigation.

As the settlers moved on out toward the midwest they found that growing season rainfall sometimes closely paralleled the water needs of the crops and bumper yields were obtained. But dry periods such as occurred in the early 1930's came along. Rainfall did not nearly meet crop needs. The soil dried out. Winds blew and a "dust bowl" developed on lands that, during wet years, were fields of waving green wheat. Such lands may produce 30 to 40 bushels of grain per acre in the good years but only 5 or 10 in the dry ones.

Upon moving farther west many of the early trappers and explorers considered the arid West worthless for agriculture since there was never sufficient rainfall on the valley floors to produce crops. However, in some of the most arid sections a civilization has existed for many, many years. These people have eked out an existence by growing crops in the valleys under a form of irrigation.

Evidence indicates the existence of a flourishing prehistoric agriculture in the Salt River Valley of Arizona and in similar valleys of the West. The agriculture practiced was adapted to the use of an "imported" water supply. This water supply is from precipitation falling on the high mountain lands not suitable for farming. Some of this precipitation is not utilized by nature where it falls but forms the rivers and creeks flowing down into the valleys. From these streams, water is obtained and put to use. Hopi, Navajo and Zuni Indians of N. E. Arizona and N. W. New Mexico still practice a crude "flood-type" irrigation that was probably developed by their forefathers many generations ago. These same people also practice a type of irrigation in areas where there are no streams and where annual precipitation may be only 12 to 18 inches. This is done by planting corn sparsely on lands that absorb precipitation rapidly. Several kernels are planted deeply in the soil at the bottom of a man-made depression. The depressions and planting points are some 6 or 8 feet apart in each direction. Any surface runoff is towards the bottom of each depression. Precipitation that is absorbed goes downward and is picked up by the spreading roots of the corn. Thus, a large part of the area serves as a "watershed" for the corn plants. The "equivalent" rainfall may be several times the 12 or 18 inches falling on all the area if plant density were taken

into consideration. Although the corn yields per acre are low in terms of what we normally like to think is good for irrigated land, the corn usually has well-filled kernels and is considered highly usable.

It is generally agreed that modern irrigation began in the United States on a real commercial scale when the Utah pioneers first reached the Great Salt Lake Valley in 1847. The parched valley lands in this general area would not produce then, nor will they produce now, without irrigation. This "new" practice spread rapidly throughout the arid West.

For some reason, applying water to lands in Arizona, California, Idaho, Colorado, Utah, etc. where rainfall was generally inadequate to meet the water needs of a crop, was called "irrigation". However, applying water to eastern lands where precipitation may more nearly meet the water needs, was called "supplemental irrigation". They are both supplemental and they are both irrigation. It is simply a matter of degree as to how much irrigation water is needed in relation to precipitation. Today, most researchers and technicians in the field of irrigation look upon the practice as being "irrigation" whether in Arizona or New Jersey.

Not all of the western United States is arid and not all of the East is humid. Within the West there is wide variation in the amount of annual precipitation and the time at which it occurs. Our coastal areas in Washington, Oregon and Northern California receive heavy annual precipitation. The higher elevations on the west faces of the Cascade and Sierra Nevada mountains receive tremendous amounts. Even the farmed valley lands of this region receive far more rainfall annually than is needed to raise crops. However, there may be several months each summer when little or no rainfall occurs. Most crops will die without rainfall or irrigation water for any extended period, and might just as well have not been planted in the first place. Thus midsummer irrigation is required, particularly for those crops that cannot go dormant but must be kept growing rapidly all summer.

Moving southeastwardly towards the high plains and central parts of Texas, it is found that rainfall comes largely in the summertime—when needed by the crops. Only sometimes it doesn't come.

In between these extremes, there are areas where it matters little whether the rainfall comes in the summer or winter—because there isn't any. The average precipitation at Yuma, Arizona, is only about 3 inches per year and at Prosser, Washington, it is only about 6 or 7 inches. Crops grown in such areas are almost entirely dependent upon irrigation to meet their water needs. However, it is interesting that many engineers feel that irrigation under arid conditions presents fewer operational problems than are found in semihumid areas.

In the more arid areas, it is relatively easy to schedule the amounts of water that must be applied each season, each month or each week. Carefully controlled amounts can then be applied to satisfy the plant needs. This is not true where rainfall meets most of the crop needs. Here one must "play the odds". Rainfall records are analyzed and the number of drouth periods normally expected each season and how long they will last is determined. The irrigation farmer purchases the recommended amount of irrigation equipment. He gets all ready to irrigate. Then, along comes a serious drouth year. The equipment is not adequate to fully meet the water needs of the crops. Or, more precipitation than normal may occur and other troubles develop. Heavy rainfall may come immediately following or during the irrigation. If soil is

wet from irrigation and will not absorb the rainfall, a serious runoff and possibly an erosion problem may develop. Surface waste-water disposal systems are "a must" on irrigated lands in the more humid climates. This is particularly true where summer rainfall intensity is high. Thus, irrigation problems may be fewer and simpler where summer rainfall is minor and where irrigation must be depended upon to meet the water needs of the plants —providing there is adequate water for irrigation.

So far, only one climatic factor that influences irrigation has been discussed. However, it is certainly the most important factor. If there is sufficient rainfall to meet plant needs, irrigation is not needed. If there is not sufficient rainfall, irrigation must be practiced or yields will be reduced.

Nature seldom cooperates to fully meet the water needs of the crops for maximum production. Too much water at any one time in a plant's life may be just as damaging to high production as is too little water. If man controls the amount applied, he can, or should be able, to make the best environment possible for plant growth. This is one of the major reasons why higher crop yields are expected under irrigation in the arid West than are expected without irrigation in the more humid East.

Precipitation also may affect crop yields in another way. In the arid West, roots of various crops usually go much deeper than do the roots of similar crops in the more humid East. Even in deep soils, uncontrolled heavy rainfall tends to drown out the deeper roots. It is possible, therefore, to utilize a greater "water storage reservoir" and "feeding zone" in the West than is possible in the East even though the soils may be equally deep in each region.

Precipitation, of course, is not the only factor affecting irrigation agriculture. Temperature, length of the frost-free period, daylight hours, humidity, wind and other factors influence crop growth.

Many crops can stand little or no frost. Thus, the frost-free period definitely limits the growing period of such crops and the longer the frost-free period, the more crops that can be grown. Small grains may mature where the frost-free period is little more than 90 days long. However, cotton should have at least 180 and preferably over 200 days between frosts. As long as plant growth occurs, water will be consumed.

Pasture grasses and, to a certain extent, alfalfa, will stand temperatures dropping below freezing repeatedly providing they don't drop too low and providing the daytime temperatures are rather high. Climates having year-long growing seasons are generally considered by most irrigationists to be the most valuable for irrigation agriculture. Such climates are better adapted to irrigated, high-value, specialty crops and are, therefore, of greater value in an irrigation economy.

Summer daylight hours vary widely as we move from the equator towards either pole. For instance, the average length of day during July at Brownsville, Texas is only 13.6 hours; whereas, it is 15.5 hours or 14 per cent greater, at Great Falls, Montana. Thus, if other influencing factors were the same, there would be considerable more daily growth and consumption of water by most crops at Great Falls than at El Paso.

Humidity affects the amount of irrigation water needed, but its quantitative effect on crops grown in most of our arid West is still unknown. If conditions are such that moisture in the air condenses out as dew, this dew may be just as effective in meeting crop water requirements as in an equal amount of irrigation water.

Wind has a major influence on evaporation from a free water surface. Under certain conditions it also may have considerable effect on the rate at which consumptive use of water by vegetation takes place, but, in general, the effect is much less than that of evaporation.

While on the subject of climate and irrigation it might be pointed out that climate not only affects irrigation, but irrigation may affect climate. Frequent, light irrigations may have a pronounced effect on the temperature of the root zone soil as well as the air temperature immediately above the irrigated crop. Also, sprinkler irrigation has been used successfully to prevent frost damage to certain crops on nights when temperatures have dropped well below freezing. In this latter case, the actual frost-free period is lengthened over what it would have been without sprinkler irrigation.

One bad effect of irrigation on climate is the result of some early spring irrigation, particularly on the high mountain meadow country of the West. In many instances, water that is ice-cold—since it melted from snow just a few miles upstream—is diverted out over the meadows and allowed to run continuously for many days. This practice tends to keep temperatures down and to slow down all bacterial and plant growth. Such a practice should be discouraged. Actual measurements in Colorado and Wyoming have shown conclusively that hay and beef yields can be more than doubled by using improved irrigation practices on the meadow lands.

Studies by the University of California show that rice production is decreased by the use of cold water. The use of warming basins has been suggested to raise the temperature of the water above 70° F before applying to the fields. A temperature of about 70° F seems to be about the lowest that the common varieties of rice will stand without damage.

In summary, it might be said that climate determines whether or not there is an irrigated agriculture. Plants grow only when the environment is suitable. This means that temperatures can be neither too hot nor too cold. It means that there must be a source of energy (sunshine) if the plant is to grow. It means that the root zone must contain the proper amounts of water, air and plant food. A super-abundance or the lack of any one of the three, may kill the plant.

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HYDRAULIC PROPERTIES OF PERFORATED WELL CASINGS

Yoash Vaadia[1] and Verne H. Scott,[2] J. M. ASCE
(Proc. Paper 1505)

SYNOPSIS

Proper selection of the perforations in well casings is important to optimum function of water wells drilled into aquifers of alluvial material. This paper deals with the hydraulic performance of well casings of varied perforation characteristics. Several commercially perforated casings were tested in combination with various gravel envelopes. Results are presented and compared with criteria already available for well screens.

INTRODUCTION

Several factors affect the cost of pumping ground water and the amount of water obtained. The characteristics of the water-bearing formation cannot be altered. Maximum efficiency will therefore depend on proper design and construction of well and pumping plant. An important factor in well efficiency is selection of the perforated casing.

Perforated well casings are pipe sections placed at the depth of the aquifer and slotted to allow water to enter the well. Casings are installed in the field in two different manners: in wells drilled with a cable tool rig, perforations are usually made after the casings are installed; in wells drilled with a rotary rig, a preperforated casing section is inserted to the desired depth.

With rotary rig installations a gravel envelope is placed around the casing and its perforated section. The envelope excludes most of the sand and other aquifer particles from the well and at the same time permits greater flow of water into the well by slightly increasing its effective diameter.

The perforated casing should meet several basic requirements: it should be structurally strong, should prevent excessive movement of gravel

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1. Research Asst., Univ. of California, Davis, Calif.
2. Colorado State Agri. & Mech. College, Fort Collins, Colo.

particles into the well, and should offer a minimum of resistance to the flow of water through it. These requirements complicate the matter of selecting perforated casing. For example, a slot of large cross section reduces resistance to flow of water but also reduces structural strength, and wide slots may permit excessive entry of aquifer particles. The design of an efficient perforated casing will necessarily involve compromise.

A distinction is usually made between well screens and perforated well casings. Though functionally the same, they differ in construction and specific use. In well screens, slots are usually smaller, sometimes forming a close mesh, for use in sandy aquifers to prevent excessive sand movement into the well. Perforated well casings are used in those alluvial aquifers where the amount of sand is relatively small. In such aquifers most of the sand which will move is usually carried out of the well in the development process or shortly after.

The selection of perforated well casing has been based largely on experience and tradition. Theories regarding the problem have been developed only recently, and little is known about the hydraulic characteristics of water flowing into wells through perforated casings.

Criteria are needed for matching gravel size and shape to perforation size and shape so as to incur the minimum head loss consistent with needed casing strength and sediment-screening characteristics.

The objective of this investigation was to study the characteristics of different types of perforated casings and gravel envelopes and to establish the relations between them. Minimal lengths are suggested for different commercial perforated casings in association with different gravel types.

The relationship of the water-bearing formation to the gravel envelope was not considered in this investigation. Several workers[1,2,3] have already studied this relationship; their criteria help the correct selection of gravel envelope for the geological formation involved.

Review of Literature

Bennison[1] makes several recommendations for the selection of well screens. He suggests that a velocity of less than 0.1-0.25 ft./sec. will keep head losses and sand movement at a minimum. It is also important to have the percentage of open area (ratio of perforated area to total surface area of the screen) as large as the porosity of the natural water-bearing formation, or larger. Otherwise, more energy is required to move the water into the well.

Considerable work on the flow of water into well screens has been done by workers at Colorado State University.[2,3] The several papers published by this group are concerned with theoretical developments and experiments pertaining to selection of well screens, selection of gravel envelopes for different conditions, and other aspects of the problem.

Petersen et al[4] postulated, and experimentally confirmed, design criteria for well screens. Their criteria are based on dimensional analysis of the factors that influence flow into wells. The relationship obtained in expressed in the following equation:

$$\frac{\Delta h}{V^2/2g} : \frac{\cosh CL/D + 1}{\cosh CL/D - 1} \qquad (1)$$

in which Δh is the difference in piezometric head between the outside and inside of the screen; V is the final average velocity along the vertical axis of the screen; A is the cross-sectional area of the screen; D is the diameter of the screen; and L is its length. C was defined as:

$$C = 11.31\ ApCc \tag{2}$$

where Ap is the ratio of the total area of the screen openings to the total surface area of the screen and Cc is the coefficient of contraction of the screen openings.

A plot of equation 1 (Figure 1) shows that the loss coefficient, $\left(\frac{\Delta h}{V^2/2g}\right)$, approaches two for values of CL/D greater than six and, as the values of cosh CL/D in equation 1 increase, the influence of the plus or minus one becomes negligible and the ratio $\frac{\cosh CL/D + 1}{\cosh CL/D - 1}$ approaches the limit of one.

The value of CL/D depends only on the characteristics of the screen. A larger value of CL/D can be obtained by (1) increasing the length of the screen, (2) increasing the percentage of open area, Ap, or (3) improving the shape of the opening in such manner as to increase the coefficient of contraction. Decreasing the diameter of the screen also increases the value of CL/D--but it reduces the capacity of the well. Equation 1 and Figure 1 indicate that the performance characteristics of a screen are not improved by CL/D values greater than 6. This is important because additional lengths of screens are costly. It also discounts the concept, held by some, that head and energy losses per unit flow are decreased with length of screen.

The above theoretical development for screens should apply to perforated well casings too, and this was shown experimentally to be the case. Some of the conclusions of Petersen et al were, therefore, used in the analyses of perforated well casings and gravel envelopes.

Theoretical Considerations

The flow of water into a well through a perforated well casing is analogous to flow through a series of orifices. Jet velocity is not developed without conversion of potential energy into kinetic energy. In this case the energy of the jet is dissipated and the water accelerates parallel to the vertical axis of the casing. In this process a dissipation of energy is involved, bringing about head loss.

Hydraulic Head Losses in Orifice Flow

Hydraulic head losses in orifice flow may conform to the following equation:

$$\Delta h = \left(\frac{1}{C_v^2} - 1\right) \frac{V^n}{2g} \tag{3}$$

where Δh is the hydraulic head loss; C_v the coefficient of velocity; and V the jet velocity. Taking the logarithm of each side and substituting V = Q/A gives:

$$\log \Delta h = \log \frac{\frac{1}{C_v^2} - 1}{2g} + n \log \frac{Q}{A} \tag{4}$$

$$\log \Delta h = n \log Q + \log \frac{\frac{1}{C_v^2} - 1}{2g} - n \log A$$

Equation 4 shows that there is a logarithmic straight-line relationship between hydraulic head loss and rate of flow. The slope of this line is equal to n and its intercept is

$$(\log \frac{\frac{1}{C_v^2} - 1}{2g} - n \log A).$$

The magnitude of the slope will not change as long as the characteristics of the perforation are such that its drag coefficient is independent of the Reynolds Number of the opening. If this condition exists, the slope will be numerically equal to two. In this study of commercially available well casings, the wall thickness is sufficiently thin that the drag coefficient is independent of N_R. Therefore, the value of n in equation 4 should be two.

The intercept of the line of equation 4 $(\log \frac{\frac{1}{C_v^2} - 1}{2g} - n \log A)$ may change with variations in the value of C_V or of the open area. At low values of Reynolds Number of the opening, viscous effects will tend to reduce the value of C_V slightly, but at high values C_V may be considered to be constant. Since the range of N_R values was kept relatively high in the experiments conducted

ducted here, the first term of the intercept $\log \frac{\frac{1}{C_v^2} - 1}{2g}$ remained constant. Any appreciable variation in the value of the intercept is caused by changes in the open area through which flow occurs. This point is of great importance. It shows that one of the major factors controlling the magnitude of head losses per unit flow is the value of the open area.

Corey(5) has shown that above a certain percentage of open area the hydraulic head losses of well screens are no longer a function of the open area. Petersen et al have shown that minimum head loss may be achieved by changing the length and diameter of the screen. Thus, for a given length and diameter of perforated casing (within certain limits), open area is the major factor controlling head losses.

Factors Controlling the Open Area

The open area of perforated well casings can be controlled in various ways. The simplest is to provide a greater number of perforations per unit area. But, as noted earlier, loss of casing strength limits this approach. Another way to increase the effective open area of the perforations is to increase the

coefficient of contraction by improving the shape of the openings. For sharp-edged slots, it has been shown that the value of Cc is $\frac{\pi}{\pi + 2}$, or 0.611.(6) Thus, flow occurs through only about 0.6 of the opening.

The magnitude of Cc for different shapes of opening can be found in most hydraulic text books.(7) The following discussion will be concerned only with the factors that affect Cc values for the types of perforations used in this investigation.

The range of values of Cc is affected by several factors, including orifice edges, thickness of edges, and orientation of mouth of opening to direction of flow. The first two factors, roughness and thickness, tend to increase Cc and decrease C_V. They do not have the desirable effect of reducing the value of the Δh intercept in equation 4. An increased value of Cc may be offset by a decreased value of C_V. The highest C_V value is obtained with smooth, relatively thin openings. With openings of this nature C_V varies only slightly with Reynolds Number and for all practical purposes remains constant. C_V is not affected by angle of opening.

Figure 2-a shows one type of perforation studied: a punched opening with smooth surfaces and relatively thin walls, approaching the definition of a sharp-edged orifice. A Cc value of about 0.61 would be expected, as indicated earlier.

Figure 2-b shows the other type of perforation studied: chiseled from inside, with lips open to the outside at an angle of about 135°. The openings, though not as smooth as those in Figure 2-a, are sharp enough to approach the conditions of a sharp-edged orifice. The Cc calculated for this type of an opening is 0.537.(8)

Extent of Plugging by Gravel

The gravel envelope around a well casing plugs part of the openings, increasing head loss per unit flow when total area of openings is a critical factor. Measuring the extent of the phenomenon was essential to this investigation although no direct method is available. An indirect one, first employed by Petersen et al, was used.

A new constant--Cp, the coefficient of the perforated casing--was required. This coefficient is the product of the coefficient of contraction (Cc) and the fraction of open area remaining open upon partial plugging by gravel $(\frac{Aa}{Ap})$. Aa is the percent of open area when gravel surrounds the casing and Ap is the percent of open area without gravel.

By definition then, $$Cp = \frac{CcAa}{Ap}$$

and $$\frac{Cp}{Cc} = \frac{Aa}{Ap} \qquad (5)$$

With no gravel around the perforated casing, Aa is equal to Ap, and Cp is equal to Cc. Assuming that Cp and Cc can be determined with and without a gravel envelope, the magnitude of the plugged area can be calculated.

Equation 2, developed for analysis without a gravel envelope, defines C, in the term $\frac{CL}{D}$, as 11.31 ApCc. The term ApCc is the effective area of the openings. With gravel around the perforated casing, Ap no longer applies;

AaCc expresses the effective open area under this condition. Since the value of Aa is unknown we substitute ApCp for AaCc, which are the same according to equation 5. Instead of equation 2 one obtains:

$$C = 11.31\ ApCp \tag{6}$$

Equation 6 is a general equation, describing conditions whether or not gravel surrounds the casing.

The value of the loss coefficient, $\frac{\Delta h}{V^2/2g}$, can be calculated from experimental data. The corresponding value of CL/D can be taken from Figure 1. The value of C in CL/D can be calculated directly, and hence the value of Cp.

The ratio $\frac{Cp}{Cc}$ in equation 5 can be obtained by determining the Cp of a perforated casing with and without gravel. Without gravel, Cp is equal to Cc. Since the above ratio is equal to $\frac{Aa}{Ap}$ the extent of open area plugged by the gravel can be determined.

Experimental Equipment and Procedure

Perforated Casings

Tests were made of two types of perforated casings (Figure 2ab) commonly used in California. Data on the casings tested are in Table I. Casings with punched perforations are designated A; those with chiseled perforations are designated B. The fractions after the letter indicate the width of slots, in inches, given by the manufacturer. All the slots were about one and one-half inches long. Each of the tested casings was 12 inches in diameter and about two feet long. The slots were equally spaced in 30 columns, five slots to a column, except that casings A-3/32 and A-1/8 had five and six perforations alternating.

Table I

Dimensions of the perforated casings tested

Casing	Length inches	Outside diameter inches	Inside diameter inches	Area of the opening inches^2	Number of openings	Percent of open area
A-3/32	22.63	12.31	12.0	0.122	165	2.29
A-1/8	22.63	12.31	12.0	0.178	165	3.36
A-3/16	22.50	12.31	12.0	0.281	150	4.85
A-1/4	22.50	12.31	12.0	0.362	150	5.63
B-3/32	22.50	12.19	12.0	0.050	150	0.88
B-1/8	22.50	12.19	12.0	0.097	150	1.69

Gravel

Three types of gravel commonly used in the Central Valley of California were employed (Figure 3). Gravels A and C, of igneous and sedimentary origin, are fairly smooth, flat stones. Gravel B, wholly of igneous origin, is round. Gravel A was sieved in the gravel pit by commercial methods between screens of 3/4 and 1/4 inch. Gravel B was sieved in the laboratory between screens of one inch and 1/2 inch. Gravel C was sieved in the gravel pit between screens of 1-1/2 and 3/4 inches.

Size distribution analysis was done by the standard weight method, using five screens with square holes of the following sizes: 1-1/2 inches; 3/4 inch; 1/2 inch; 1/4 inch. The three different gravels used in the experiments were sieved through these screens and the amount retained of each was considered to be a size greater than the screen size. Results are shown in Figure 4.

Experimental Apparatus

Figure 5 shows a schematic diagram of the test apparatus: a metal tank, 2 ft. tall and 5 ft. in diameter, covered with a lid secured to the tank by a set of bolts. The casing to be tested was placed in the center with a rubber gasket on each end. A screen around the casing at a distance of 9 inches contained the gravel used in gravel tests. Water was delivered to the tank by turbine pump, through a 6-inch pipe manifold connected at four inlets 1 ft. above the bottom of the tank. Each was baffled by a metal plate inside the tank. This arrangement provided uniform axial distribution of the flow into the perforated casing.

Two valves controlled flow and pressure: one near the pump governed inflow; one on the outlet governed outflow. A set of bleeders facilitated the escape of any entrapped air.

Pressure distribution was determined by piezometer tubes: a set of four through the wall of the tank, two 6 inches and two 18 inches from the bottom of the tank; a set of four on the outside of the casing; a single piezometer in the center of the casing; and several others at various locations within the tank to verify pressure readings. All piezometers were connected to a manometer board.

The outlet discharged downward through an 8-inch opening centered in the bottom of the tank, the water flowing by gravity through an 8-inch pipe into a baffled weir box. Discharge was measured by a 90° V-notched weir. The hook gage for determining head measured to one thousandth of an inch.

Procedure

After the casing was positioned, the piezometers (3/16-inch copper tubings) were inserted into 1/4-inch perforated standard pipe sections, welded to the bottom of the tank. The piezometers were passed through their respective compression fittings in the lid as it was secured, and were connected to the manometer board. Glass wool in these connections dampened any pressure fluctuations. Precautions were taken to avoid entrapped air within the tank.

Data collected consisted of manometer readings and corresponding flow rates. Measurements for each casing were made without gravel as well as with each of the three gravel types.

Each test included ten to fifteen readings for a range of flows between

about 0.1 cfs and 1 cfs. A reading of the manometers was accepted if it did not change within 5 minutes. It had been determined that the readings established at 5 minutes did not change later.

Discussion of Results

Head losses across perforated casings at various flow rates are presented, together with other data, in Figures 6-11 and Tables II-IV.

Hydraulic Head Loss as a Function of Flow

Hydraulic head loss of flow through perforated casings (head difference between piezometers 2 and 1, Figure 5) as a function of rate of flow is plotted logarithmically in Figures 6-11. Each of these figures expresses the relationship for tests without gravel and tests with gravels A, B, and C. In general the results agree with the theoretical development given previously for flow through orifices. The slope expressing relationships between flow and head loss is nearly constant for all tests. The least head losses per unit flow were found in the tests without gravel, in which actual open area is the largest, for each perforated casing.

The slopes of the lines in Figures 6-11 are listed in Table II. The expected theoretical slope value of two is approached closely. Some uncontrolled variables may be the reason that most of the values are slightly smaller than two. The results in Table II express slopes of free-hand tendencies.

TABLE II

Slope of the lines expressing the relationship of loss coefficient vs flow

Casing	No gravel test	Gravel A test	Gravel B test	Gravel C test
A-3/32	1.93	1.92	1.99	1.91
A-1/8	2.00	1.98	1.99	1.96
A-3/16	1.99	1.97	1.96	1.98
A-1/4	1.99	1.95	1.91	1.98
B-3/32	2.08	2.00	2.01	2.00
B-1/8	2.03	1.98	1.98	1.98

The Effect of Reynolds Number on Slope Value

The minimum Reynolds Number for all casings was about 1,000 at lower flows (around 0.15 cfs) and 7,000 at higher flows (around 1.0 cfs). Calculation of these was based on velocity of flow through the openings, width of the openings, and viscosity of the water at 20°C. The relationship between Reynolds Number and Cq (the product of Cc and Cv) has been plotted by Vennard.[9] The value of Cq is 0.75 at N_R 1,000 and 0.65 at N_R 7,000. In equation 7 it was shown that a change of Cv or Cc changes A and therefore changes the h intercept, $\log \dfrac{\frac{1}{C_v^2} - 1}{2g} - 2 \log A$, of the lines in Figures 6-11. The increased value of Cq from lowered N_R is a result of decreased Cv and increased Cc at lower velocities. Since the Cc increase is dominant, the intercept at lower flows will be smaller than that at higher flows. As a result the slope of the line will be steeper than if such variations in Cc did not occur. This may explain the values greater than two obtained for the slopes of casings A-3/32 and A-1/8 without gravel. All other slopes are two or smaller.

The Influence of Effective Diameter

Water velocity through the slots may account for the small slope values obtained. The magnitude of this factor is very difficult to estimate. The velocity of water movement through perforations has a decided effect on effective diameter (the diameter of the area in the center of the casing through which flow actually occurs) because of the greater distance that jets of higher velocities shoot into the casing. Equation 4 is correct as long as Q/A is equal to V. In the cases studied—because of variations in effective diameter—Q/A was not equal to the average velocity in the casing. The velocity calculated from flow and the cross sectional area of the casing is lower than actual velocity. The cross sectional area through which flow occurs decreases with increasing flows; the greater the flow the greater the error in the value of the velocity calculated from Q/A. This situation does not duplicate the condition on which equation 4 is based. If A, the cross section of the casing, is assumed to be the A value of equation 4, an increasingly larger value of A than the actual one is assumed with increasing flow rates. This in turn progressively moves the points of the plots to the right, producing a flatter slope than that expected. Equation 4 is not satisfied under the conditions of varying areas because such changes cause velocity to change. A corresponding correction to flow or cross sectional area is impossible.

The tendency of Cq variation to increase the slope is more than offset by the influence of the effective diameter variations. This accounts for the slight deviation of the slope below the expected value of two. It is probable that when gravel does not surround chiseled casings the effective diameter of the casing is not changed significantly by the shape of the openings. This may be responsible for the slight positive deviation of the slope of these casings.

Results

Assuming a theoretical value of Cc for each type of slot, the calculated value of CL/D for all casings was below the critical value of 6, because of the short sections tested and the relatively small percent of open area. Therefore it was anticipated that head losses in these casings would be

greater than minimum possible values. The values of CL/D for the casings tested ranged from 0.1 to 1.0. Figure 1 indicates that this range is within the sloping region of the curve. This fact enables one to study the changes produced by various gravel envelopes in the CL/D and the coefficient of contraction.

Punched Casings

Figure 6 presents head losses at various flow rates in casing A-3/32. Slot size, according to the manufacturers, was 3/32" x 1-1/2", but accurate measurement showed the slots to be smaller. Slot area was 0.122 sq. inches; open area was 2.29%, the lowest value among the punched casings. It is expected that head losses per unit flow will be greater for this casing than for others of the same type. Head loss at flow of 0.5 cfs was about 6 inches without a gravel envelope. The greatest plugging was produced by gravel A, which changed head loss to 15 inches at a flow of 0.5 cfs, more than double that obtained without gravel. Gravel B did not produce a marked increase in head loss, and gravel C raised head loss to 8 inches at the same flow.

It should be recalled that gravel A is smallest, C is largest, and B is roundest. The smallest gravel, A, plugged more area, for it had better access to the openings. But shape is important, too. Though gravel B was smaller than gravel C, it plugged less of the slots because its rounder shape blocked less area and permitted water to flow through the greater interstices. The flatter particles of gravel C packed more closely and plugged more of the perforation area.

Figure 7 presents relationship of head loss to flow for casing A-1/8, which had an open area of 3.36%. The trend is similar to that for casing A-3/32, but with smaller head losses. The larger size of slots is responsible. Gravel type affected head loss as with casing A-3/32, with one variation: a slight leftward shift of the line for gravel B indicates a greater head loss per unit flow than with the larger gravel C. It is to be expected that the round gravel B would plug more area as slot size increased.

Figure 8 shows the head loss relationship of casing A-3/16, which had an open area of 4.85%. Head losses for this casing were much smaller than for the other two type-A casings. Head loss for gravel A was about the same as with casing A-1/8 although the larger slots would be expected to plug more extensively. A slightly different gravel arrangement around casing A-3/16 may account for the discrepancy. The relationship of gravel C was reversed by the larger slot: the round, smaller gravel plugged more area than did the flatter, larger gravel. The smaller openings in the first two casings allowed shape to more than offset the effect of size.

Casing A-1/4 had the largest slots tested, specified as 1/4" x 1/2" with an area of 0.326 square inch. Open area was 5.63%. Because of the larger open area, all head loss values were lower for this casing than for the others. Head loss with rounder gravel B was greater than with flatter gravel C (Figure 9). At a given flow the difference in head loss between gravels B and C with casing A-1/4 was greater than the difference between these gravels with casing A-3/16. This may be attributable to the larger open area.

Chiseled Perforations

It has been shown that the coefficient of contraction is lower for chiseled perforations than for the punched type, with consequently greater head loss. It is important to note that the two casings tested of this type had smaller perforations than the dimensions specified by the manufacturers: 3/32 x

1-1/2 inches for casing B-3/32 and 1/8 x 1-1/2 inches for casing B-1/8. Plasticine impressions showed that actual width was only about one half the specified width. Area of opening was 0.050 square inches for casing B-3/32 and 0.097 square inches for casing B-1/8. The percentages of open area were 0.88 and 1.69, respectively.

Since coefficient of contraction and percent of open area are both very small for these casings, head losses are much higher than with the punched casings. For example, casing B-3/32 at 0.5 cfs flow had a head loss of more than 50 inches without gravel. Casing B-1/8 at the same flow had a head loss of about 15 inches.

The interesting point is that gravel did not plug the openings appreciably. When head loss is plotted against flow (Figures 10 and 11) the results without gravel and with gravels A, B, and C fall approximately on the same line. However, gravel tests produced some greater head loss than tests with no gravel, and gravel A had a slightly greater head loss per unit flow than did gravels B and C.

It was indicated previously that the smaller the area of the slot the less area is plugged by a given gravel type. Although the area of the chiseled perforations is very small, it seems unreasonable that this fact alone can account for the comparative independence of results from type of gravel. An explanation can be found in the slight protrusion of the lips of chiseled perforations. It is probable that gravel particles in the angle of the lips extend beyond them, preventing other particles from blocking the opening. However, if the perforations had been wider, it is almost certain that gravel would have plugged some of the open area.

Summary of Results

A tabulation of the mean loss coefficient and the corresponding CL/D for all casing and gravel combinations is presented in Table III. The value of the loss coefficient was calculated on the basis of head losses determined experimentally and averaged velocities along the vertical axis of the casing. No corrections were made for changes in effective diameter. The experimental values of CL/D were taken from Figure 1 by calculating loss coefficient from the experimental results. Calculated CL/D values were based on assumed coefficients of contraction (0.611 for punched perforations and 0.537 for chiseled perforations), percent of open area of the various casings, casing length, and casing diameter. The loss coefficients presented in Table III are directly proportionate to the head losses shown in Figures 5-11. The greater the loss coefficient (above two) the greater the head loss per unit flow. Therefore the discussion on the data in Figures 6-11 applies equally to the loss coefficient results in Table III. This table makes evident the trends established by the relationship of gravels to head loss for various slots.

Table IV shows the values of Cc and Cp, the ratio Cp/Cc, and the minimum length of casing necessary to keep head loss at a minimum in each case. Cc values were calculated from the experimental values of CL/D in tests without gravel. Values for the punched casings averaged 0.624, which approaches conditions with sharp-edged orifices. The slight deviation may be attributable to errors in measuring percent of open area and to other experimental error. Slight deviation probably results from effective diameter changes, which affect loss coefficient and, in turn, the CL/D value. The magnitude of this effect is not known; it will vary with different slot sizes. However, as discussed earlier, the effect is so small as to be considered negligible.

TABLE III

Values of loss coefficient and CL/D

Casing	Mean loss coefficient				Experimental CL/D values				Calculated CL/D
	No gravel	Gravel A	Gravel B	Gravel C	No gravel	Gravel A	Gravel B	Gravel C	
A-3/32	97.2	260.4	103.6	135.0	0.290	0.173	0.278	0.241	0.304
A-1/8	39.2	104.6	51.30	60.6	0.465	0.277	0.390	0.366	0.445
A-3/16	18.6	112.64	37.98	30.2	0.670	0.267	0.475	0.530	0.637
A-1/4	16.1	46.4	26.66	21.8	0.720	0.418	0.556	0.620	0.740
B-3/32	762.4	877.2	769.6	836.6	0.102	0.036	0.101	0.097	0.0997
B-1/8	234.4	313.9	225.2	287.6	0.186	0.160	0.188	0.166	0.192

Cc for the chiseled perforations was 0.549 for casing B-3/32 and 0.524 for casing B-1/8, agreeing closely with the theoretical value of Cc, 0.537, for this type of opening. Cp was not very different from Cc, indicating that very little of this type of perforation was plugged by the gravels tested.

Table IV lists the minimal lengths of the different casings for least flow resistance with different gravel types. Calculation of these lengths was based on the concept of CL/D discussed earlier. They express the length of perforated casing needed for CL/D value of 6. Minimal length will vary with type and size of perforation and size and shape of gravel.

The loss coefficients obtained in tests of all the casings without gravel were plotted against the calculated values of CL/D in Figure 12, using the theoretical Cc indicated before. Agreement is very good with the curve drawn from theoretical equation 1, which is further evidence of the validity of this equation in the range investigated.

CONCLUSIONS

1. Several commercially available perforated casings were tested for hydraulic performance. The effect of three common types of gravel envelopes on performance of the casings was investigated.

2. It was shown that established criteria for the selection of well screens applies to the casings tested.

3. Chiseled casings of the type tested are less efficient than punched casings for a given short length of casing.

4. Size and shape of gravel have great influence on the plugging of openings in perforated casings. For best performance, size should be large and uniform, and shape should be spherical.

5. Chiseled casings are not plugged by gravel as much as are punched casings. Tests with larger chiseled openings, comparable in size to the punched openings tested, should be carried out to establish the importance of size of opening.

6. Perforated casing coefficients are presented that facilitate calculation of minimum length necessary for optimal operation of perforated casings and gravel envelopes. Minimal length is calculated for the casings and gravels studied.

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TABLE IV

Values of Cc, Cp, and minimal casing length

Casing	Cc	Cp			Cp/Cc - Aa/Ap			Minimal length in feet			
		Gravel A	Gravel B	Gravel C	Gravel A	Gravel B	Gravel C	No Gravel	Gravel A	Gravel B	Gravel C
A-3/32	0.593	0.354	0.590	6.493	0.597	0.959	0.831	39.1	65.43	40.7	47.0
A-1/8	0.650	0.390	0.550	0.530	0.600	0.846	0.815	24.3	40.5	34.5	29.8
A-3/16	0.650	0.263	0.462	0.516	0.404	0.711	0.794	16.8	41.5	23.6	21.1
A-1/4	0.603	0.350	0.465	0.519	0.580	0.771	0.861	15.6	26.9	20.3	18.2
B-3/32	0.549	0.517	0.544	0.522	0.941	0.931	0.951	110.0	117.0	111.0	116.0
B-1/8	0.524	0.447	0.530	0.463	0.853	1.011	0.883	59.9	70.3	59.2	67.7

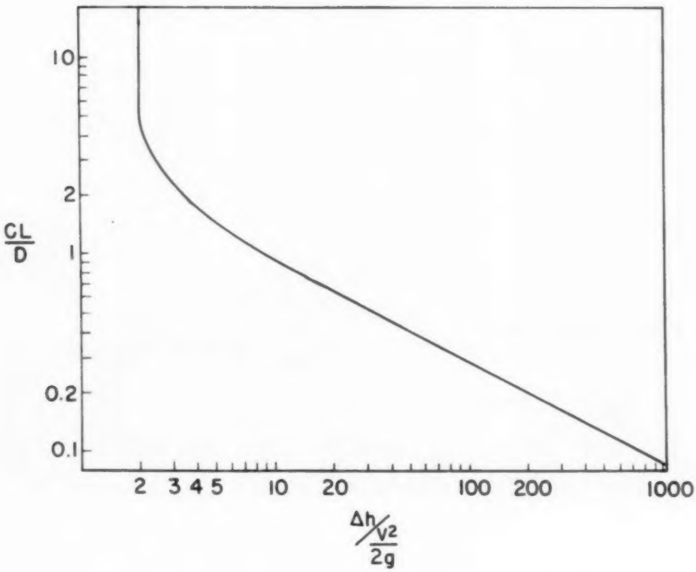

Figure 1. The loss coefficient as a function of CL/D

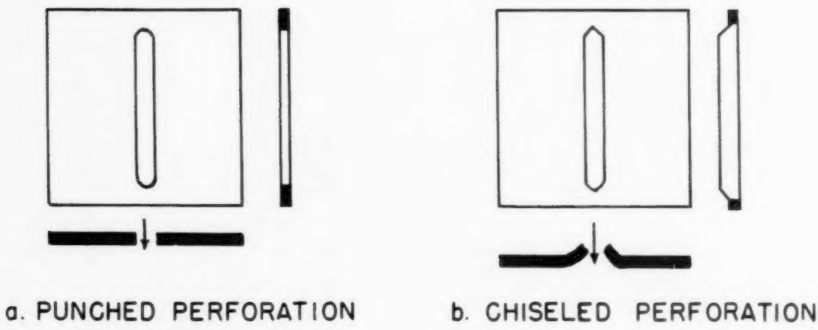

Figure 2. Sections of the type of perforations tested

Figure 3. Types of gravel

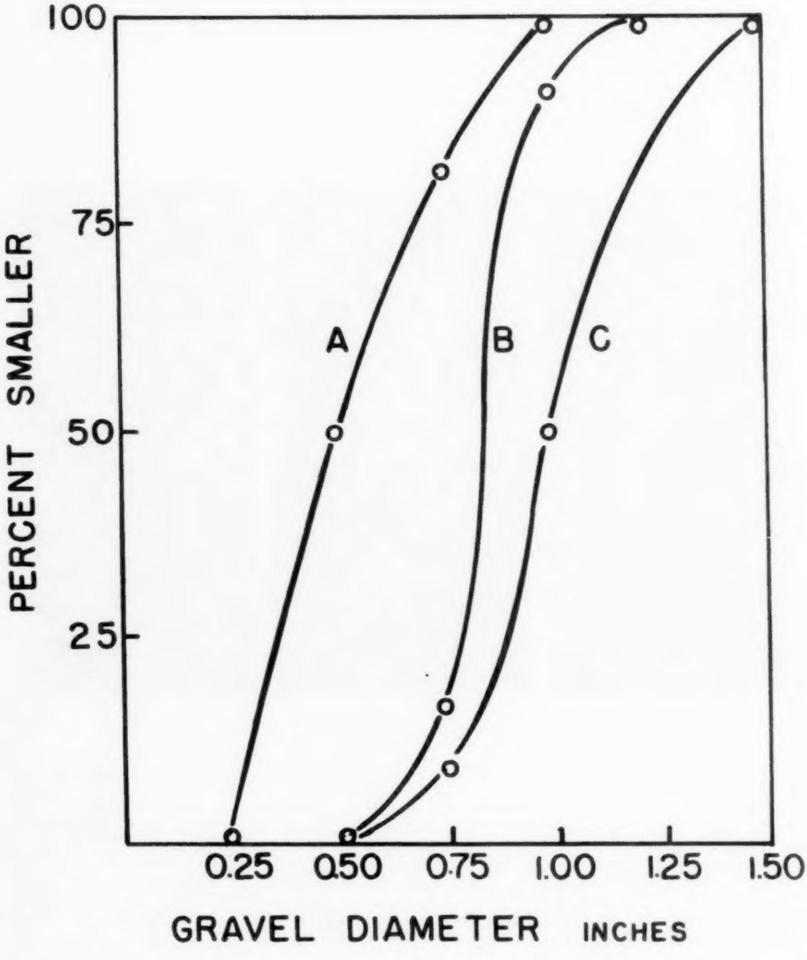

Figure 4. Gravel size distribution

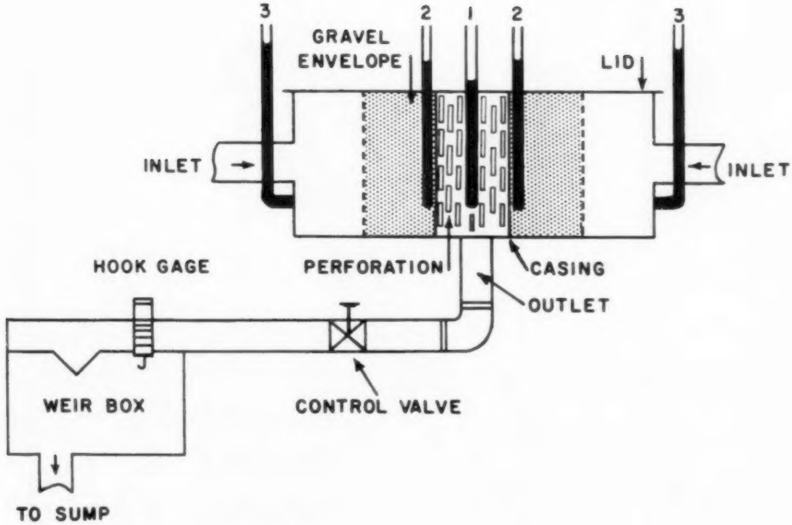

Figure 5. Schematic diagram of experimental apparatus

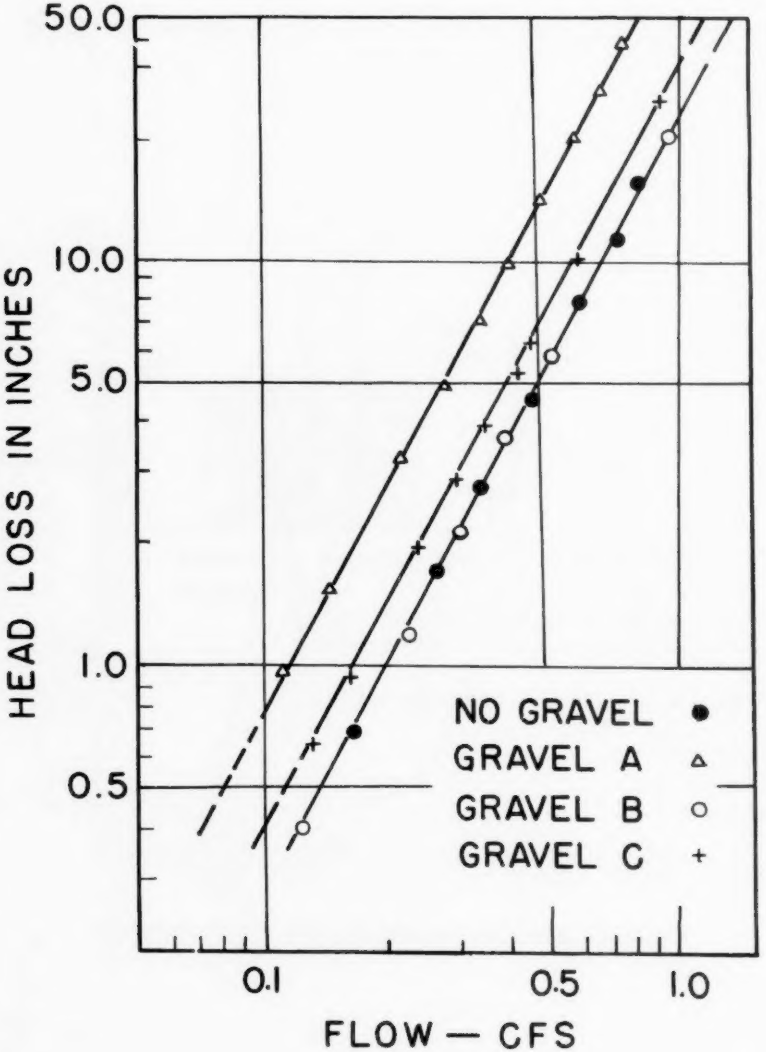

Figure 6. Head loss vs. flow for casing A-3/32

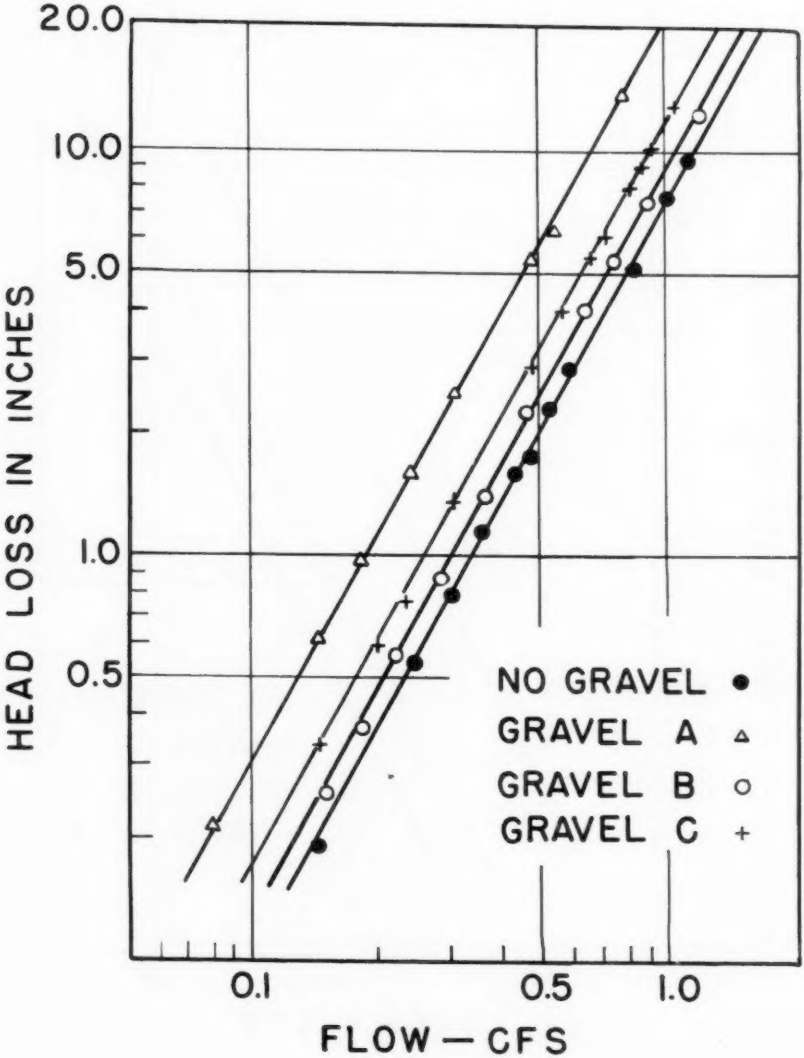

Figure 7. Head loss vs. flow for casing A-1/8

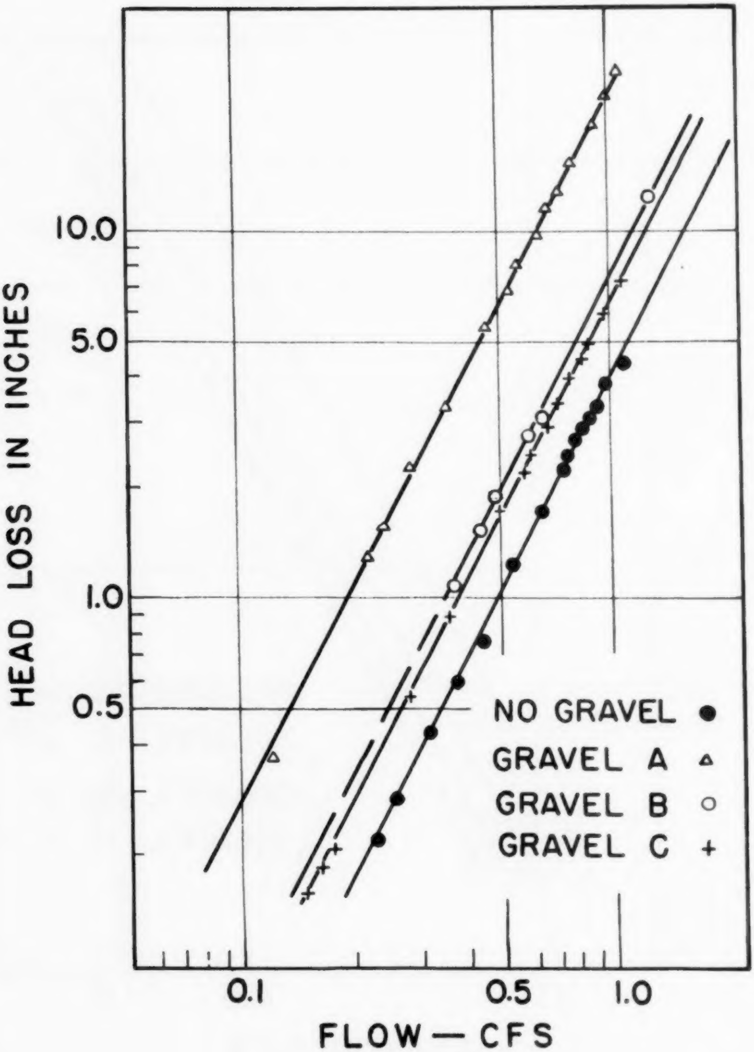

Figure 8. Head loss vs. flow for casing A-3/16

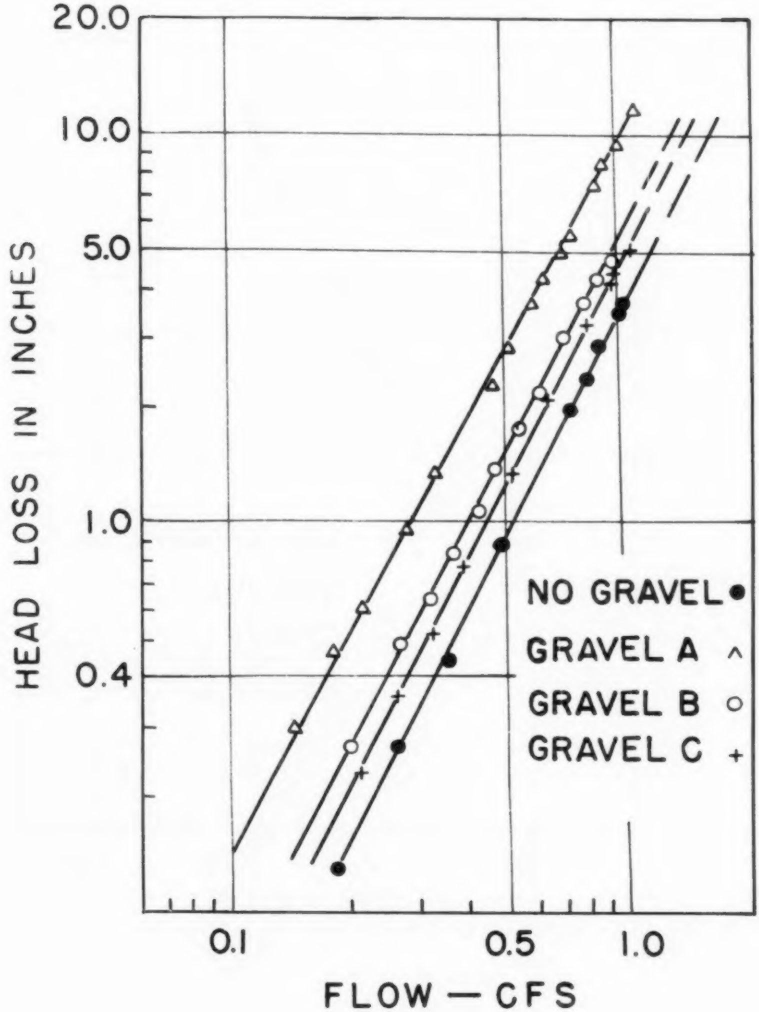

Figure 9. Head loss vs. flow for casing A-1/4

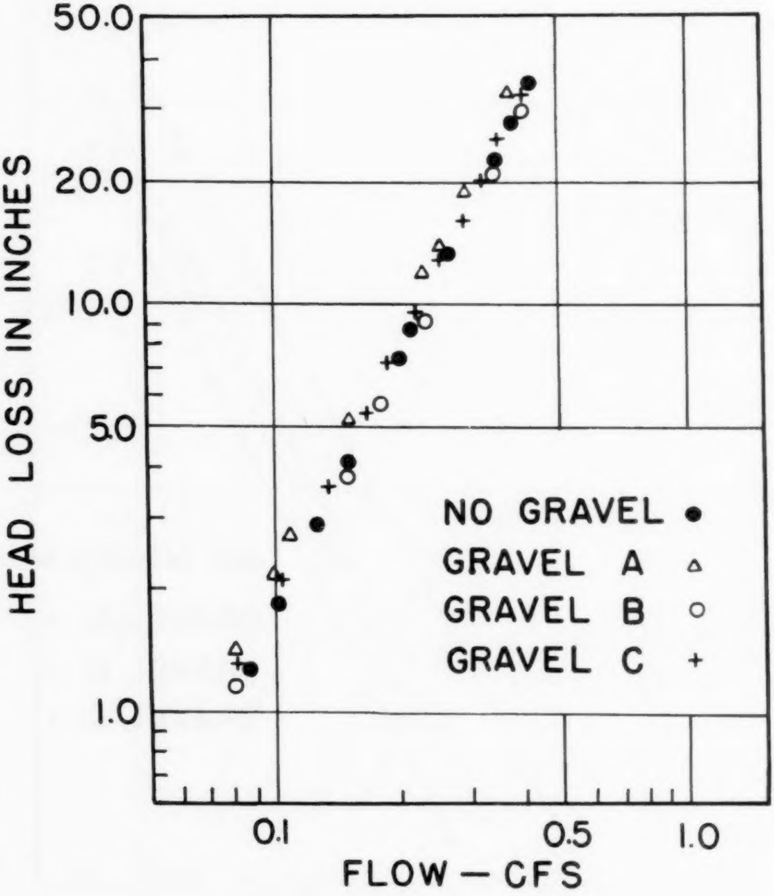

Figure 10. Head loss vs. flow for casing B-3/32

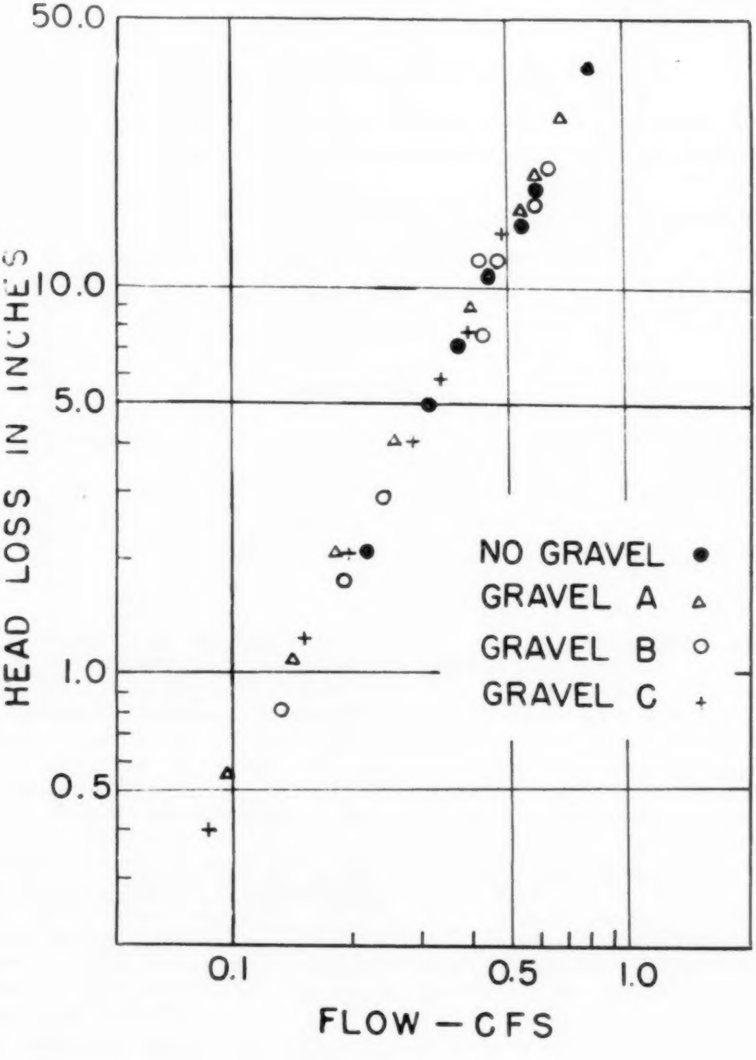

Figure 11. Head loss vs. flow for casing B-1/8

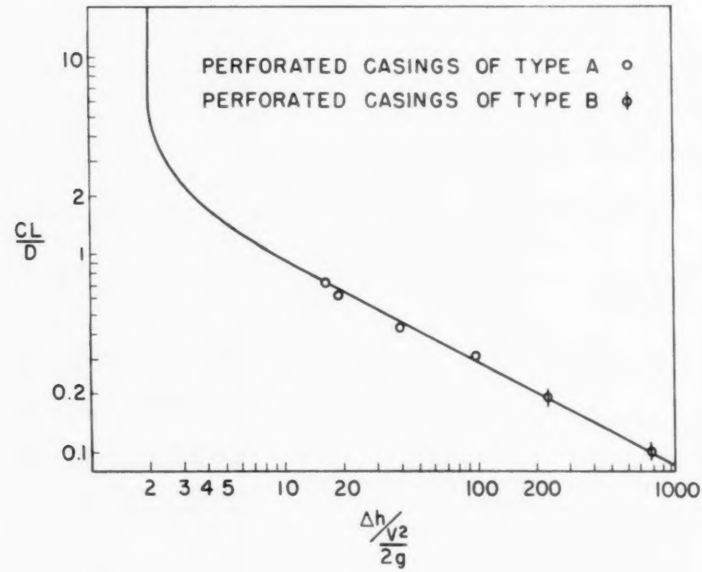

Figure 12. Experimental CL/D values for the various casings tested compared with curve of Figure 1

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DRAINAGE IN RELATION TO A PERMANENT IRRIGATION AGRICULTURE[a]

C. R. Maierhofer[1]
(Proc. Paper 1506)

ABSTRACT

After trying and often failing for some 5,000 years to establish a permanent irrigation agriculture in arid lands, man finally has the knowledge and tools to assure success. Inadequate drainage and modern technology of selecting lands for permanent productivity under irrigation are practical answers.

The answer to the question, "Can man develop a permanent irrigation agriculture?" is definitely "yes," but there are some reservations, and certain conditions must be met if it is to hold true.

Drainage in irrigation is a very large subject, a subject so important in irrigation agriculture today that it enables many millions of human beings to eat and stay alive. As drainage of irrigated lands becomes understood by more people, and if the understanding is implemented to the limits of our modern concepts and knowledge, it will contribute to the well being, dignity, and happiness of many millions more of starving, miserable people in underdeveloped parts of the world where there is not sufficient rainfall to provide their basic clothing and food requirements. In the future, as our population swells and our land resources shrink, drainage of irrigated lands will be a tool for providing new human comforts in now prosperous irrigated areas. There is a limit to additional irrigation development. Inevitably, we will have to face that fact, and then we must improve productivity which we now consider ideal, or starve.

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a. Paper presented at First Intersociety Conference on Irrigation and Drainage, San Francisco, Calif., April 30, 1957.

1. Chief, Office of Drainage and Groundwater Eng., U. S. Bureau of Reclamation, Denver, Colo.

To present drainage and its place in a permanent irrigation agriculture effectively enough to leave an impression that may stimulate its use, an engineer or applied scientist must depart from his world of detailed precision and become a philosopher. If I knew, it would require years to tell you "how," but perhaps in 30 minutes I can tell you broadly "why." I will attempt to give you my thoughts on a subject that has long intrigued me, a subject that has stimulated my curiosity constantly to seek answers as to what is permanent in irrigation and what is not, which lands can be successfully drained and which cannot, on which lands should we spend great sums for storage works and irrigation development, and on which lands can we predict that our investments in such works would be lost and the lands permanently ruined.

Undoubtedly some of you, particularly those from humid regions, believe I am overemphasizing the importance of drainage in permanent irrigation. Others may feel that I am writing of something that does not concern you; something that you neither want nor need. Please hear me:

> Who among you has seen the vast, desolate areas of water-logged lands in the valleys of the Tigris and the Euphrates?
>
> Who has seen the salinized lands in the plains of the mighty Indus, so great in extent that 50 million people would not go to bed hungry each night if these potentially high-productive lands, now barren and white with salt, were adequately drained?
>
> Has your well-fed heart ever been pierced by the sore, sand-cut eyes of the utterly unfortunate human seeds that remain in the Seistan Basin of the ancient Helmand, where once broad reaches of fertile and productive irrigated lands supported great civilizations before Alexander the Great and Genghis Khan?—these lands that are now water-logged, salinized, and terribly eroded, that would still be green and fertile had the elements of drainage been known to the irrigators of that day—Who has seen these lands and the people that exist there?
>
> In the Western World, have you seen pleasant villages in Mexico and Canada become agricultural slums because ground water rose too high in irrigated lands, or because salines became so concentrated in the root zone that plants wilted and died?
>
> Have you known an irrigation farmer of western United States who sold his water-logged, sodium saturated farm for whatever he could get, after he had invested his life's savings in it, so that he could pay the costs of taking his family to another place where he could feed them?

The drainage engineers who have been called to go to such places and try to find solutions to the problems have seen these things—they quickly learned the importance of <u>permanence</u> in irrigation agriculture. Many of you have seen similar sights—many others I am sure do not comprehend them. I am not trying to frighten or alarm you. I am simply trying to tell you that where man has not developed, where he cannot develop, or where he does not have the knowledge to develop permanent irrigation agriculture, desolation sooner or later will prevail as surely as it prevails after wars or disease epidemics. Conversely, where man has not exploited the land, and where he has been able to develop a permanent irrigation agriculture, there is satisfaction, health, happiness, a sense of attachment to the land. There are no enemies—there are full stomachs and a warm sense of participating in the human race. So much for the importance of drainage.

To discuss the permanence of anything, some definitions and some limitations are essential, for we know positively of no resource that is permanent.

For you and me to be on common ground, for us to understand one another, requires that I analyze the principal elements of my subject as they relate to each other. These elements are "Drainage," "Irrigation Agriculture," and "Permanence."

"Drainage" is the removal of excess water and excess salines from agricultural soils. Surface drainage is the removal at the surface of excess precipitation and of irrigation wastes. Its purpose is to prevent flooding and to minify the more costly subsurface drainage requirements. Efficient engineering designs of surface drains require only an understanding of topographic conditions and of open-channel hydraulics, and sometimes of pumping. Effective surface drainage is comparatively inexpensive, and is essential to permanence of irrigation agriculture. So much for surface drainage!

If soils are otherwise suitable for plant growth—

> that is, if water of suitable quality and sufficient quantity is available to apply to the soil, if water can readily enter the soil, if the soil can store water and plant nutrients, and if the soil has the physical and chemical characteristics which allow water freely to move laterally or vertically through it so that air can enter after the capillary reservoir is filled—

but if too much water or too much salt, or both, are present to allow plants to grow, then the environment for plant growth can invariably be improved by subsurface drainage. The environment can be improved to the extent that excess water or excess salines are no longer detrimental, after which other limitations of productivity become more important than drainage. In rare cases, natural subsurface drainage adequately removes the excess water and salts. I have seen only two such cases, both in small areas. Natural drainage is never adequate in river plains or lake sediments. To generalize, the excess water and salts must always be removed artificially.

Drainage should be economically feasible. If it cannot stand on its own with respect to benefits accrued, it does not contribute to permanence of irrigation. With certain few exceptions, related to extremely adverse but readily recognizable physical and chemical characteristics of some soils, successful subsurface drainage is always limited only by the costs. In desert lands, whose people could not be fed without irrigation agriculture, the economic limitation of expenditures for drainage would be very high. It would be equivalent to the cost of the alternative source of food after the lands were no longer productive, which would be the cost of imported food. For semihumid lands with reasonable amounts of fairly well distributed precipitation in most years, the economic limitation of expenditures for draining irrigated lands would be quite low. It would equal the cost of producing food without irrigation.

For this discussion, the element "Irrigation Agriculture" is the practice of agriculture for optimum, perennial productivity on lands which could not support the food needs of man without artificial application of water. It is necessary to draw this distinction because the subsurface drainage considerations and costs connected with the irrigation of humid area lands, where irrigation is supplemental to rainfall and where salines are usually not a problem, are very different from those of lands in arid regions. Although the permanence of the productivity of irrigated lands in humid or semihumid areas is usually a safe conclusion, the widespread feasibility of this practice has not yet stood the test of time. In arid lands, the salines in the soil, in

the irrigation water from surface streams, and in the ground water, make the subsurface drainage problems different and more costly to control. The introduction of capillary forces into the equation, the translocation of salines in the ground water, and the higher evapo-transpiration add to the complexity of irrigation agriculture. Also, the human element in the form of diverse irrigation practices, some of which are detrimental to productivity, based often more on fancy than on fact, make the picture of arid region irrigation agriculture still more involved.

In humid area irrigation agriculture, the subsurface drainage requirement objective is to remove ground water from the root-zone soils so that shallow rooted crops can aerate and develop better root systems, and so the land will be warmer and can be worked earlier in the spring. In arid-region irrigated lands, the drainage objective is to provide similar aeration also, but usually for deeper rooted crops, and to control the ground-water table, its capillary fringe, and the lateral and vertical movement of percolated irrigation water in which salines are dissolved, so that deposition of salines cannot occur in the root zone soil.

The last element to clarify in my subject is "Permanence." It is probably the most ambiguous and the most elusive physically, because history has not furnished sufficient data to distinguish between intermittent, partial irrigation and constant, complete irrigation for optimum productivity. There is a great difference in the effect on soil deterioration. To be permanent, any operation such as irrigation agriculture, need not be economically feasible for all periods in history. The resource, land, upon which the operation depends must be constantly usable, but not necessarily used constantly. The resource should not permanently deteriorate. It should be suitable for use or susceptible to being prepared for reuse during those times in history when it is economically feasible to use. This means that, even if irrigated lands may once have become salinized or waterlogged to the extent that they were no longer productive and to the extent that the costs of reclaiming them by drainage were not justifiable during a given era, the development of a permanent irrigation agriculture on them is not precluded if they can be feasibly reclaimed at a later period in history. I think there are at least 100 million acres of such lands today; potentially good lands, in which we can develop a feasible and permanent irrigation agriculture as future needs require.

Drainage is an integral part of a permanent irrigation agriculture. Subsurface drainage can keep good lands in permanent productivity, and it can reclaim potentially good but salinized or water-logged lands for permanent productivity. I have been able to find no contrary evidence. That is why I answer "yes" to the question which is the theme of this conference: "Can Man Develop a Permanent Irrigation Agriculture?" However, some lands are not potentially good. They do not have soils with suitable physical or chemical characteristics for permanence. Such lands cannot be drained at a feasible cost; some of them cannot be drained at any cost. However, they are valuable in that they open the door of modern technology of land selection for permanent productivity under irrigation, because they have taught us where permanent irrigation agriculture cannot succeed.

I would like to give you my general ideas relative to—"what is basically required in a permanent irrigation agriculture?" to which I add "in relation to drainage," and then the qualification, "in an arid region environment."

Soils must have productive capacities at least equal to the costs of production, including costs for subsurface drainage. They must be

suitable for diversified cropping, including deep rooted crops and all crops climatically adapted. Subsoils must have open structure, to allow ready penetration of roots, air, and water, and the escape of excess water.

Subsoils and substrata must not have excessive exchangeable sodium in the first 5-foot depth.

Irrigation water must be of a quality that will permit good plant growth.

Water must be applied in sufficient quantities to provide plant evapotranspiration requirements and sufficient deep percolation to prevent and remove saline accumulations. Water must be uniformly applied so that some parts of the field do not become water-logged while plant and leaching requirements are not fulfilled in other parts. This means that effective irrigation is not possible without infiltration of excess water and without surface waste. Thus, permanent irrigation requires storage and water distribution systems capable of delivering large enough quantities of water rapidly enough to accomplish these things, and surface and subsurface drainage systems capable of preventing saturation of the plant root-zone soils.

Irrigation water must be applied often enough to prevent capillarity from bringing ground water to the surface from the water table. The movement of water, and thus of salines, must always be downward and laterally away from the plants. It is not always safe to depend upon depth to ground water to assure that upward capillarity does not become operative. Capillarity can be prevented from moving salts upward only by frequent irrigations, sometimes oftener than plants require. In the great Indian Desert, I have seen evidence that capillary forces acted from a static water table through 30 feet vertically, constantly depositing salts on the surface of potentially excellent lands, which had long been abandoned.

Inadequate surface drainage and excessive leakage from canals can usually be compensated for by subsurface drains, but it is axiomatic that water can be prevented from entering the soil at much less cost than it can be withdrawn from the soil by subsurface drains after it has entered.

Necessary in all but very rare instances are effective systems of deep outlet, branch, collector, and lateral drains.

Sometimes, when substrata and aquifer conditions are ideal, subsurface drainage may be more inexpensively accomplished by pumped wells or recharge wells.

As important to the permanence of irrigation as any of the foregoing is constant, effective maintenance of drain systems. The most important element of maintenance in a subsurface drain is its originally designed effective depth. Effective drain depth is the distance from the ground surface to the water surface in the drain, not the distance from the ground surface to the bottom of the drain.

Equally important with respect to drainage in irrigation agriculture are those things which do not contribute to permanence in arid, saline environments.

Subsoils and substrata within practical depth of drains cannot be heavy textured. Capacity for hydraulic conductivity is not great enough

in such soils, and noncapillary pore space is too small for them to be drained at feasible cost. Rare exceptions might be heavier soils with unusually good structures. I have seen some along the Mediterranean and the Caribbean. However, neither area was truly arid, although some salines were present in both.

Lands having soils derived from shales are very poor risks for permanence. The subsoils, almost without exception, inherently are heavy, very slowly permeable, intractable clays.

Lighter subsoils and substrata in environments of high exchangeable sodium cannot usually be feasibly drained. I have encountered subsoils composed of 85-percent sand, with zero permeability. While dispersed soils caused by excessive sodium have in some cases been successfully treated at the surface, I have never seen such soil structures permanently improved at depths greater than about 20 inches. I do not consider that high concentrations of neutral salts affect the permanence of irrigation.

Poor structure in any substratum within practical deep drain depth is a distinct deterrent to successful irrigation agriculture. The exceptions are where interspersed strata of high permeability sands or gravels exist. I have heard that dispersed soils have been permanently improved at depths below 30 inches. I have looked for such cases, but have never seen them. I think it has been accomplished at great cost in Southeastern Europe, but only temporarily.

Shallow soils over slowly permeable substrata are not conducive to permanent irrigation. Although such lands usually can be drained with closely spaced shallow drains, diversified cropping is not possible and income from shallow rooted crops has not generally been great enough to pay the costs of efficient irrigation and drainage through economic cycles. There are some exceptions in areas where there is a ready market for high value, luxury crops.

Permanent productivity under irrigation has not been possible where there is upward artesian leakage, except where there are more or less continuous sandy or gravelly horizons between the confined aquifers and the root zone of plants. These highly permeable horizons must be penetrated with subsurface gravity drains, or with pumped wells.

There are exceptions in connection with my subject to which I have not found answers—perhaps some reader can explain them.

I have seen lush crops growing in some areas, not in others, where artesian pressures were constantly pushing saline ground water into the root zone, and we have all seen the remarkable plants of the sea, which thrive in a saline environment. As I interpret them, our standards say this is not possible. Perhaps these plants could be developed so that permanent irrigation would be possible under saturated, saline conditions.

I know that most plants require aerated root zones; yet, I have seen upland trees growing at the water's edge in constantly saturated soils along perennial ponds.

I have seen soil amendments applied in great quantity, in accordance with our best scientific procedures, to sodium saturated soils for over 20 years, with practically no success. Adjacent, on similar lands, an

unscientific, hard-working immigrant applied manure for fewer years with great success. In similar soils in other places, soil amendments succeeded where manure would not.

What is the answer? All I know is that manure worked better in one place than calcium chloride and gypsum, and that the reverse happened in another place. One thing to me is certain—nature tends to adapt to whatever happens, and we should not take ourselves so seriously that we forget to try to learn what happened, so that we can apply the knowledge to our own welfare. It is probably good that we do not have all these answers, because if we did, we would cease to learn.

I have long felt that we need to know a great deal more than we do about the effects of climate on capillarity and resulting tolerances of plants to water-table depths and salines. I am certain that when irrigated lands in most of western United States, and elsewhere in the arid regions of the world, had ground water as near the surface as do some irrigated lands of the Mediterranean and Caribbean areas, or had such high concentrations of salines and alkalis, their productivities did not support the costs of irrigation. In most parts of the United States today we would not consider the development of some of these lands for permanent irrigation. Perhaps this is principally because we are limited by water and not by land; hence, better lands can usually be found on which to use a given water supply. Or, perhaps, the things we know do not permit permanent irrigation are unimportant in areas with year-round growing seasons, comparatively heavy rainfall though seasonal, continually warm temperatures, and high humidity, all conducive to maximum microbiological activity in the soil. I have been led to these conclusions and feel sure that ground water can be nearer the surface and salinity concentration tolerances are higher under such conditions. While crops on high water-table lands and highly salinized soils can never be as good as they could if the ground water and the salts were not present, they definitely are better in these semitropical areas than in areas of the world where desert conditions prevail. Peculiarly, I have seen similar phenomena in semihumid lands at latitudes of about 50° north, although the latter had extenuating conditions and harmful manifestations seemed to be cumulative, though slowly so.

In contrast to the above conditions, there are abandoned desert lands in the Middle East with much better soil characteristics, by our present standards of measurement, where no plant life has been able to survive. Not only differences in temperature, humidity, and rainfall, but the physiological effects on the plant of consumptive use, aeration of the root zone, and salines under different conditions of temperature and humidity seem to offer the only means of rationalizing these extremes.

Our present concepts of the phenomena connected with irrigation, including drainage and what transpires as water and salts enter and move through soil, may or may not be reliable for forecasting the permanence of an irrigation agriculture. We think we have the final answers on many things. I am sure man through the ages has always thought he had the final answers. This is human nature. However, it isn't easy today to find a simple theory that has endured for a century, much less to find one that is permanent.

Nevertheless, I conclude with the firm opinion that man can develop a permanent irrigation agriculture, and that our standards for classifying lands for permanent productivity under irrigation are sound. We fail only when we

dream of permanence on lands or with water of a quality or quantity where we should know better. Then we suffer the economic and sociological consequences.

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METHODS OF COMPUTING CONSUMPTIVE USE OF WATER

Wayne D. Criddle[1]
(Proc. Paper 1507)

ABSTRACT

Consumptive use of water is a term and concept rapidly becoming accepted in the field of hydrology, water supply and utilization. The author has summarized the more generally used methods for computing consumptive water requirements of crops. He has also included certain data and charts that may somewhat simplify the application of the methods.

INTRODUCTION

During the past quarter century, hydrologists have given increasing recognition to the "consumptive use" concept. This term is now commonly used when talking about water supply, irrigation, drainage, industrial and municipal uses, litigation over water rights and many other uses.

Even the layman is beginning to think of water uses as being either consumptive or non-consumptive. All recognize that development of hydroelectric power, water transportation, washing and cooling although essential and useful, do not consume the water. It is still available for other useful purposes. Other uses such as irrigation, consume a large portion of the water diverted. This consumed water (water changed from a liquid to vapor form or actually retained in the plant tissue) is not available for reuse until it has gone through the hydrologic cycle and precipitated back to earth.

For many years, the U. S. Department of Agriculture and the various State Experiment Stations have been studying the problem of how much irrigation water is required for crops grown under different conditions of climate, soils,

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1. Utah State Engr., formerly Irrig. Engr., Western Soil and Water Management Branch, Soil and Water Conservation Div., Agri. Research Service, U. S. Dept. of Agri., and Prof. of Civ. and Irrig. Eng., Utah State Univ., Logan, Utah.

cropping patterns, water supply and other conditions. Obtaining an exact figure for each crop under each field condition is impossible since the rates of use can be changed by man. Under laboratory or experimental conditions, it is possible to maintain more or less ideal fertility and moisture levels in the soils and to have a perfect stand. Under these conditions, water consumption will be high and somewhat uniform. Under actual field conditions, at least on any practical scale, such perfection may never be possible. Thus, we get different values under controlled or laboratory conditions and actual field tests. Also, even though we do get a good field figure, higher producing varieties of crops, improved fertilization and other management practices increase yields with a resultant increase in water consumption by the crop.

Nevertheless, both laboratory and field studies must be conducted if we are to understand the effects of the various factors on water needs. A knowledge of the ranges of increases in water requirement because of heavy fertilization, higher moisture levels and denser plant population is important.

Total Water Requirement

A measure of the total amount of water consumed by a crop is only part of the picture in so far as irrigation needs are concerned. Apparently the plant has little or no preference as to how it gets moisture providing it does get it when and as needed. Thus, a knowledge of the amount of "Effective precipitation" or that precipitation contributing towards the consumptive needs of the crop becomes important in designing an irrigation system and providing a supply of irrigation water. Effective precipitation can only be estimated by taking into account the amount, intensity and distribution of the precipitation, the infiltration rate and the water holding capacity of the soil, the slope of the land and its cover.

Various researchers have studied the problem and developed general ideas as to the amount of rainfall that might be considered effective under certain specified conditions. Some have suggested that storms of less than one-half inch should be neglected since moisture will not go far enough into the soil mantle to be effective. They maintain that small amounts of precipitation will be quickly lost by evaporation without satisfying any of the consumptive needs of the crops. Others report that a rainfall, regardless of how small, is effective in reducing the rate of use of soil moisture by the plants. Thus, there are still differences of opinion on what the consumptive water requirement of a crop is and how effective the precipitation is in meeting this requirement. From the standpoint of irrigation water diversions, these differences are usually small and might be neglected without changing the results materially. Conveyance and application losses are often far greater than the total consumptive irrigation water needs of the crops.

Average values of consumptive use of water by crops may be used for design and other purposes with reasonable safety even though our knowledge of this subject is not complete. Refinements are inevitable with increased knowledge.

Estimating Consumptive Uses

Obviously it is impractical to measure consumptive water requirements of crops under all conditions of climate, soil, water supply, and management practice and at all locations. Such measurements are expensive and time

consuming. Thus, various methods have been developed for transferring measured data from one location to other locations. The measured data are correlated with climatic factors that are readily available and the estimates for other areas are based on these relationships.

The methods so far developed and generally used for measuring and transferring consumptive use data might be grouped into three general categories:

1. Empirical relationships between experimental data and various climatic and water supply data.
2. Theoretical methods based on the physics of the vapor transfer process.
3. Theoretical methods based on the physics of energies involved.

It is felt that many engineers and others working in the field of hydrology are familiar with one or more of the methods commonly used for estimating consumptive use and water requirements but that few are fully familiar with all of the generally used formula. As a result, there are often differences of opinion as to which formula might be used best with the data available and applied to the specific conditions and needs. Thus, a brief discussion of several of the better known methods follows. Their use is illustrated in the Appendix. In some instances the author has taken the liberty of making certain adaptations that may or may not be in full agreement with the thinking of the developer of the method. Nevertheless, it is believed that from this brief summary and the examples of use, one can get a general idea of what is involved in each method of computation.

Empirical Methods

Under the empirical category might be grouped the following methods:

(a) Lowry-Johnson(1)

This method is used to estimate valley consumptive use for agriculture based on a linear relationship between "Effective heat" (the accumulation, in day degrees, of maximum daily growing season temperatures above 32° F.) and consumptive use.

Consumptive use in a valley or drainage area involves water losses from non-agricultural parts of the area as well as agricultural lands. The Lowry-Johnson method requires the determination of an "equivalent valley area" of agricultural lands in order to arrive at the estimated annual consumptive use rate. The method was not originally designed for purposes other than estimating valley consumptive use on an annual basis. However, in Appendix 1 the author has made an estimate of the valley consumptive use rate for July at Boise, Idaho by adapting the method simply on a ratio of July heat units to the total annual heat units.

(b) Thornthwaite(2)

Thornthwaite assumes that an exponential relationship exists between mean monthly temperature and mean monthly consumptive use. The relationship is based largely on experience in the central and eastern United States. No allowance is made for different crops or other land use. The use of this method is illustrated in Appendix 2.

(c) Blaney-Criddle(3)

Consumptive use is found by multiplying together mean monthly temperature, monthly per cent of annual daytime hours and the crop coefficient. Crop coefficients have been developed from experiments which related consumptive use to the climatic data. Most of this work was done in the Western

United States. The coefficients are quite similar for many close-growing crops but vary widely between such crops as citrus orchards and rice or bananas. The use of this method is illustrated in Appendix 3.

(d) Hargreaves Method[4]

This method is based upon the following assumptions: (1) That evaporation of water is a physical process and can be computed. (2) That an empirical relationship exists between computed evaporation and consumptive use of water by various crops.

Mean monthly temperature, mean monthly relative humidity at noon and length of the days of the month are taken into consideration in computing evaporation. Monthly daytime coefficients for latitudes from 5^{0} to 50^{0} N. and general climatic factors for all of the United States taking into account relative humidity have been worked out so that the method can be used even though humidity data are not available for a specific locality.

Consumptive use for a specific crop is assumed to vary directly with the evaporation potential. Empirical monthly coefficients relating evaporation potential and consumptive use of water by some 29 specific crops grown at Davis, California, of sugar cane grown in Puerto Rico and of bananas grown in the Dominican Republic and in Jamaica have been worked out.

The various coefficients and an example in the use of this method is presented in Appendix 4.

(e) Other

Various other methods of estimating consumptive use have also been suggested. Correlating consumptive use of agricultural crops with evaporation from open pans or from other types of evaporimeters has been used. Additional weather factors such as relative humidity and solar radiation in the relationship have been tried by many. However, either because of lack of data at those places where estimates are needed, or because of the questionable improvement in the accuracy of the estimates, some of these proposed methods have not been widely used to date.

Vapor Transfer Method

This method assumes that the moisture flow through a layer of air near the ground or water surface can be measured. It requires simultaneous measurements of wind velocity, temperature and vapor pressure at different heights above the surface.

Formulas developed so far, although perhaps theoretically sound, generally are not practical for field use because the variables have to be measured with extreme precision. Instruments to make such measurements are still under development. Also, temperature and vapor pressure conditions change when dry land is placed under irrigation. Thus it is difficult to use the method in the planning of new projects.

Energy Balance Method

With this method the assumption is made that the energy received by a surface through radiation must equal (1) the energy used for evaporation, (2) heating the air, (3) heating the soil, and (4) any extraneous or advective energy. For short periods such as daily and monthly balances, the latter two items may be neglected without seriously affecting the accuracy.

The application of this method requires the estimating or measuring of the energy received by a surface and deciding how this energy will divide between

heating of the air and evaporation of the water. Distribution has been assumed to take place according to the so-called "Bowen ratio", a fraction depending on temperature and vapor pressure at the surface and at some height above it.

In 1948, Penman[5] of England, suggested a method of estimating or measuring the amount of radiative energy gained by the surface which he expresses in mm. of water evaporated. The method has been used widely in England and some in Australia and the eastern part of the United States. The use of this method is illustrated in Appendix 5 with certain adaptations made by the author.

Uses Made of Consumptive Use Data

Many uses are being made of consumptive use of water information and the list of uses is growing each day. In our foreign aid program, United States technicians are taking consumptive use figures and methods of estimating water requirements to many countries of the world. Holland uses the consumptive use theory in determining how much drainage water must be pumped from her "Polder" or reclaimed sea lands. Egypt is using such figures to compute irrigation water requirements for the Sinaii peninsula.

India and Pakistan are basing their irrigation and drainage project developments on consumptive use values, part of which are transferred from this country. Water requirements for irrigation developments in Japan are being based on the consumptive use theory.

Division of rivers between nations, states and local users is made on a basis of consumptive use. Hydroelectric power production must take into account the changing consumptive uses of water along the river system and their effect on the water supply available for power production.

Fish and Wildlife agencies are finding the need for consumptive use of water figures in connection with their refuges. Consumptive uses within a city are studied to determine their effect on water supply and disposal systems and their operation.

Public administrators of water rights must understand and utilize the theory of consumptive use. Many of the river systems most highly developed for irrigation are dependent upon part of the water diverted at a point returning to the stream to meet the rights of users downstream. If upstream consumptive uses increase, frequently not all of the rights downstream can be met. Instead of water rights being assigned on a blanket diversion allocation of so many acre-feet per acre or so many acres per c.f.s. State Engineers are now considering the basic consumptive irrigation requirement and allowing only this requirement plus reasonable conveyance and application losses.

Thus, many uses are now being made of consumptive use information. Our figures on irrigated crop needs are far from exact. Such figures may never be precise due to changes that are always taking place. However, it is believed that consumptive use of water figures available today are much more accurate than our efficiency figures in irrigation or our ability to forecast what the effective precipitation will be for any one year. Undoubtedly, this "relative accuracy" is the reason for the rapid increase in adoption of the consumptive use theory. In irrigated areas where water supply is generally not the limiting factor in the amount of water consumed, consumptive use of crops is being estimated with reasonable accuracy.

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APPENDIX 1

Lowry-Johnson Method

Although the Lowry-Johnson method was not developed to estimate monthly use nor individual crop uses, it is interesting to see the results for July at Boise using a simple proportion of monthly heat units to annual heat units.

The approximate relationship, $U = 0.8 + 0.156F$, is used in estimating the valley consumptive use by the Lowry-Johnson method, where:

U = Consumptive use in acre feet per acre
F = Effective heat in thousands of day degrees.

The effective heat-day-degrees F. at Boise as used by Lowry and Johnson in their original paper was 8940. The consumptive use was 26 inches. Taking July only, the mean maximum temperature in $^{\circ}$F. is about 88. Thus, the effective heat would be $(88 - 32)\ 31 = 1736^{\circ}$ F. By proportion, average consumptive use for the entire valley during July would be $1736/8940 \times 26 = 5.1$ inches depth.

Perhaps use of water by alfalfa during July might be 1.5 times the average use in the valley or 7.7 inches depth.

APPENDIX 2

Thornthwaite Method

Monthly values of heat index are related to monthly temperatures in Appendix figure 2.1. This relationship is used to determine the seasonal Heat index value shown in Appendix table 2.1. This value of 43.3 was plotted on Appendix figure 2.2 for Boise, Idaho. A straight line drawn from the "Index point" through this "Heat index point" gives the relationship between temperature and evapo-transpiration.

With a July temperature of 72.5° F. (22.5° C.) the uncorrected potential evapo-transpiration is about 11.5 cm. This potential use is corrected for sunlight and days of the month from Appendix table 2.2 using a latitude of approximately 44° N.

The average computed consumptive use of all crops during July at Boise, Idaho, is $11.5 \times 1.30 = 15.0$ cm. or 5.9 inches.

APPENDIX 3

Blaney-Criddle Method

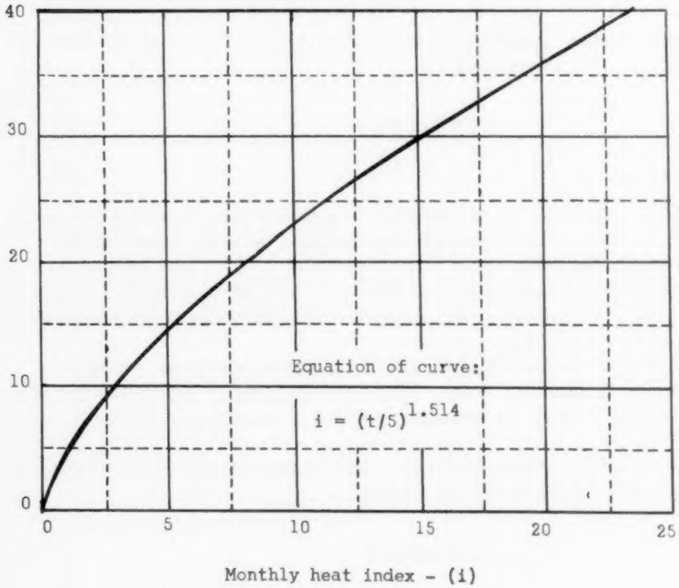
Briefly, the Blaney-Criddle method correlates measured consumptive use of water data with monthly temperatures (t), monthly percentage of day-time hours (p), and the crops' growing period or irrigation season. The coefficients so developed for different crops (see Appendix table 3.1) are used to translate or transpose consumptive use data from one location to others in which climatological data alone are available.

Expressed mathematically, the relationship used by Blaney-Criddle is:

$$U = KF = \Sigma kf$$

Where

Appendix figure 2.1. Monthly values of Heat Index, i, for use in computing evapo-transpiration by Thornthwaite Method

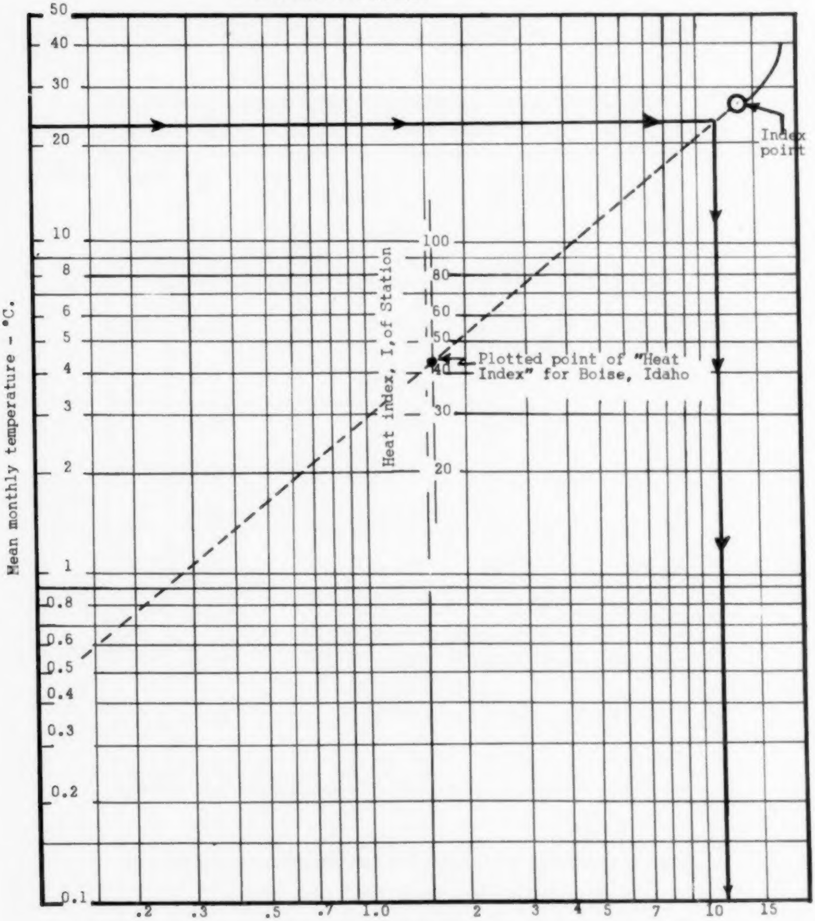


APPENDIX TABLE 2.1 COMPUTATION OF "HEAT INDEX" FOR BOISE, IDAHO

Month	Temperature		Heat Index
	°F	°C	i*
January	27.9	-2.2	0
February	33.6	1.0	0.5
March	41.4	5.2	1.0
April	49.1	9.5	2.5
May	56.1	13.3	4.0
June	64.5	18.0	7.0
July	72.5	22.5	10.0
August	71.0	21.6	8.5
September	61.2	16.3	6.0
October	50.1	10.0	2.8
November	39.7	4.3	1.0
December	30.4	-1.0	--
Annual			43.3

* Obtained from Fig. 2.1

Appendix figure 2.2 Nomograph for computing monthly evapotranspiration by Thornthwaite method



Appendix table 2.2. Mean possible duration of sunlight in the northern and southern hemispheres expressed in units of 30 days or 12 hours each

N. Lat.	J	F	M	A	M	J	J	A	S	O	N	D
0	1.04	.94	1.04	1.01	1.04	1.01	1.04	1.04	1.01	1.04	1.01	1.04
10	1.00	.91	1.03	1.03	1.08	1.06	1.08	1.07	1.02	1.02	.98	.99
20	.95	.90	1.03	1.05	1.13	1.11	1.14	1.11	1.02	1.00	.93	.94
30	.90	.87	1.03	1.08	1.18	1.17	1.20	1.14	1.03	.98	.89	.88
35	.87	.85	1.03	1.09	1.21	1.21	1.23	1.16	1.03	.97	.86	.85
40	.84	.83	1.03	1.11	1.24	1.25	1.27	1.18	1.04	.96	.83	.81
45	.80	.81	1.02	1.13	1.28	1.29	1.31	1.21	1.04	.94	.79	.75
50	.74	.78	1.02	1.15	1.33	1.36	1.37	1.25	1.06	.92	.76	.70

U is the consumptive use of water by the crop in inches for any period;
K is the empirical consumptive use coefficient (see Appendix table 3.1), and
F is the sum of the monthly consumptive use factors, $\frac{t \times p}{100}$ (see Appendix table 3.2 for values of p).

Consumptive use for July at Boise, Idaho, may be obtained from the nomograph, Appendix figure 3.1. The average July temperature at Boise is 72.5° F. The latitude is 43°54'N and p = 10.49 from table 3-2. The seasonal K for alfalfa from table 3-1 is 0.85. For the month of July, k is estimated at 0.95. From the nomograph, U = 7.23 inches.

APPENDIX 4

Hargreaves Method

The relationship between evaporation, temperature and length of day is given by the theoretical equation:

$$e = m(t-32) \tag{1}$$

In which,

e = monthly evaporation in inches
m = an impirical factor
t = mean monthly temperature in °F.

Formula (1) can be refined by correcting for the time element and expressed as

$$e = cd(t-32) \tag{2}$$

In which, c is a climatic factor depending upon humidity and, to a minor degree, upon wind movement. d is a monthly daytime coefficient dependent upon latitude.

Calculated monthly daytime coefficients, d, are given in Table 4-1 for latitudes 5° to 50° North.

By disregarding the effect of wind movement, it is assumed that the climatic factor, (c) influencing the removal of water vapor is a function of mean monthly relative humidity.

$$c = 0.38 - 0.0038h \tag{3}$$

where h = the mean monthly relative humidity at noon.

Equation (2) becomes

$$e = d(0.38 - 0.0038h)(t-32) \tag{4}$$

The relationship between mean monthly relative humidity at noon and values of c are shown in Figure 4-1. Where humidity data are not available, the factor, c, can be approximated from Figure 4-2.

Consumptive use for a specific crop is assumed to vary, directly with the consumptive use potential. Expressed mathematically:

$$U = KE = \Sigma ke \tag{5}$$

In which U is the consumptive use of a crop in inches for a given period; E is the sum of the monthly evaporation for the period. K is an empirical

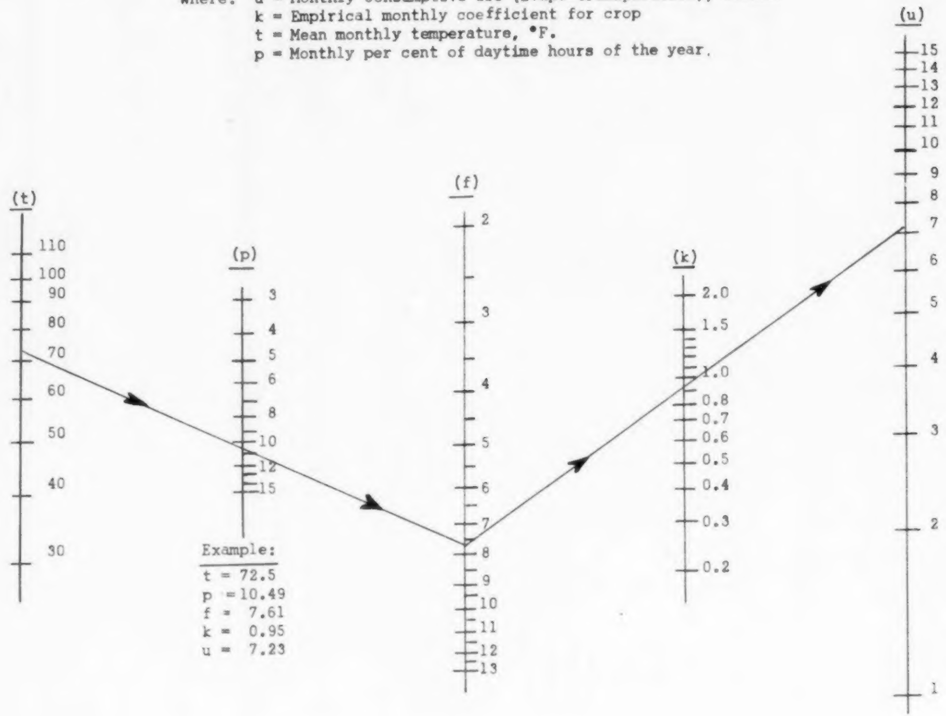
Appendix table 3.1. Normal seasonal consumptive-use coefficients for the more important irrigated crops of the West

Item	Length of growing season or period	Consumptive use coefficients Seasonal (K)	Maximum Monthly 1/ (k)
Alfalfa	frost-free	0.85	0.95 - 1.25
Beans	3 months	0.65	0.75 - 0.85
Corn	4 months	0.75	0.80 - 1.20
Cotton	7 months	0.70	0.75 - 1.10
Citrus orchard	7 months	0.60	0.65 - 0.75
Deciduous orchard	frost-free	0.65	0.70 - 0.95
Pasture, grass, hay annuals	frost-free	0.75	0.85 - 1.15
Potatoes	3 months	0.70	0.85 - 1.00
Rice	3 to 4 months	1.00	1.10 - 1.30
Small grains	3 months	0.75	0.85 - 1.00
Sorghum	5 months	0.70	0.85 - 1.10
Sugar beets	5½ months	0.70	0.85 - 1.00

1/ Dependent upon mean monthly temperature and stage of growth of crop.

Appendix figure 3.1. Nomograph for solution of Blaney-Criddle consumptive use formula $u = kf = k(tp)$

Where: u = Monthly consumptive use (Evapo-transpiration), inches
k = Empirical monthly coefficient for crop
t = Mean monthly temperature, °F.
p = Monthly per cent of daytime hours of the year.



Appendix table 3.2. Monthly percentage of daytime hours of the year for latitudes 24° to 50° north of Equator

Month	Latitudes in Degrees North of Equator													
	24	26	28	30	32	34	36	38	40	42	44	46	48	50
January	7.58	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17	5.98
February	7.17	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42	6.32
March	8.40	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27	8.25
April	8.60	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18	9.25
May	9.30	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53	10.69
June	9.20	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71	10.93
July	9.41	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80	10.99
August	9.05	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89	10.00
September	8.31	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44	8.44
October	8.09	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51	7.43
November	7.43	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22	6.07
December	7.46	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86	5.65
Annual	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

coefficient depending upon the individual crop grown. Monthly values of evaporation and crop coefficients are represented by e and k respectively.

Monthly and seasonal coefficients computed from data at Davis, California are given in Table 4-2. Also, coefficients for bananas computed from data gathered in the Dominican Republic and Jamaica and for sugar cane grown on the South Coast of Puerto Rico are given in Table 4-3.

Example of Use of Hargreaves Method

The mean July temperature at Boise, Idaho, which is at a latitude of 43°54'N., is 72.5° F, and mean monthly relative humidity for noon is 43 per cent. From Figure 4-1 e is 0.24 and d from Table 4-1 is 1.27.

Thus, $e = cd(t-32)$

$= 0.24 \times 1.27\ (72.5 - 32) = 12.3$ inches.

Normal consumptive use of water by alfalfa at Boise, Idaho during July can be computed with the Hargreaves formula, $u = ke$.

Assume $k = 0.70$ then

$u = 0.70 \times 12.3 = 8.61$ inches.

APPENDIX 5

Penman Method

The following three formulas are used by Penman in estimating evapo-transpiration:

1. $H = R_A\ (1-r)\ (0.18 + 0.55\ n/N) - \sigma T_a{}^4 (0.56 - 0.092 \sqrt{e_d})\ (0.10 + 0.90n/N)$

2. $E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098\ u_2)$ and

3. $E_T = \dfrac{\Delta H - 0.27\ E_a}{\Delta - 0.27}$

Where:

H	= Daily heat budget at surface in mm. H_2O/day
R_A	= Mean monthly extra terrestrial radiation in mm. H_2O/day
r	= Reflection coefficient of surface
n	= Actual duration of bright sunshine
N	= Maximum possible duration of bright sunshine
σ	= Boltzman constant
	= 2.01×10^{-9} mm./day
σT_a^4	= mm. H_2O/day (see Table 5-3)
e_d	= Saturation vapor pressure at mean dew point (i.e., actual vapor pressure in the air) mm hg
E_a	= Evaporation in (mm.) H_2O/day
e_a	= Saturation vapor pressure at mean air temperature in mm. Hg
u_2	= Mean wind speed at 2 meters above the ground (miles/day)[1]
E_T	= Evapo-transpiration in mm H_2O/day

1. Wind measurements taken at other heights can be corrected to the 2 meter elevation by use of the formula, $u_2 = u_1 \times \left(\dfrac{\log 6.6}{\log h}\right)$

TABLE 4-1

CALCULATED MONTHLY DAYTIME COEFFICIENTS, (d), FOR USE IN THE HARGREAVES FORMULA

North Latitude in Degrees	January	February	March	April	May	June	July	August	September	October	November	December
5	1.01	0.91	1.02	0.99	1.03	1.00	1.03	1.03	0.98	1.02	0.98	1.00
10	0.98	0.89	1.02	1.01	1.05	1.03	1.06	1.05	0.99	1.00	0.95	0.97
15	0.96	0.88	1.01	1.01	1.08	1.06	1.08	1.06	0.99	0.99	0.93	0.95
20	0.93	0.87	1.01	1.02	1.10	1.08	1.11	1.08	0.99	0.98	0.91	0.92
25	0.91	0.86	1.01	1.03	1.12	1.11	1.13	1.09	1.00	0.97	0.89	0.89
30	0.88	0.84	1.00	1.05	1.14	1.14	1.16	1.11	1.00	0.96	0.86	0.86
35	0.85	0.83	1.00	1.06	1.17	1.17	1.19	1.12	1.00	0.94	0.84	0.82
40	0.81	0.81	1.00	1.08	1.20	1.21	1.23	1.14	1.01	0.93	0.81	0.78
45	0.77	0.79	0.99	1.09	1.24	1.26	1.27	1.17	1.01	0.91	0.77	0.74
50	0.72	0.76	0.99	1.11	1.28	1.32	1.32	1.20	1.01	0.89	0.73	0.68

Figure 4-1. CLIMATIC FACTORS

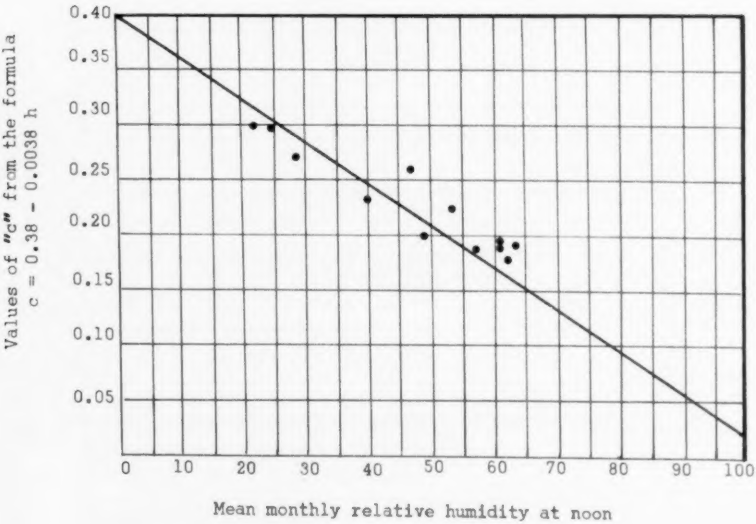


Figure 4-2. CLIMATIC CLASSIFICATIONS

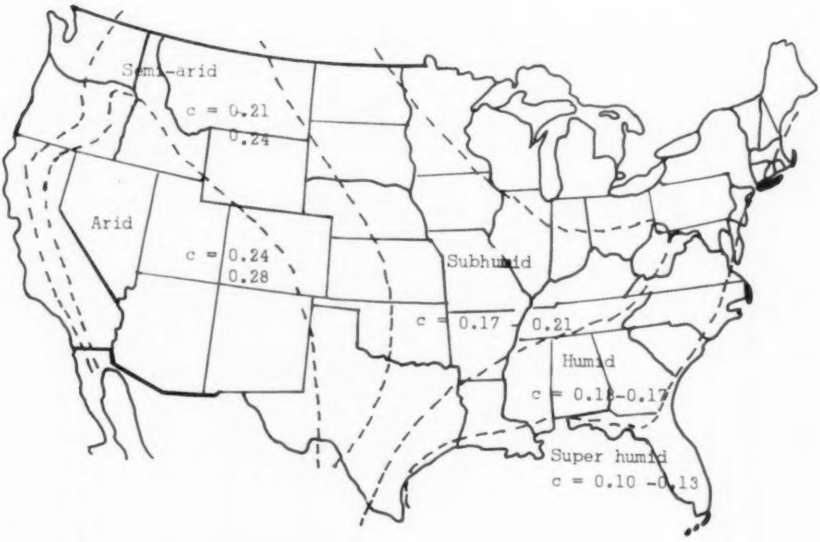


TABLE 4-2. CONSUMPTIVE USE COEFFICIENTS FOR USE IN THE HARGREAVES FORMULA AT DAVIS, CALIFORNIA

CROP	MONTHLY CONSUMPTIVE USE COEFFICIENTS "k" a/ March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	SEASONAL COEFFICIENT "k"
Alfalfa	0.41	0.70	0.64	0.67	0.74	0.67	0.64	0.40	0.41	0.59
Almonds	0.16	0.36	0.34	0.52	0.48	0.34	0.29	0.48	0.21	0.36
Asparagus	0.16	0.11	0.12	0.18	0.46	0.81	0.84	0.99	0.51	0.46
Beans (Lima				0.41	0.51	0.61	0.32			0.46
Beans				0.15	0.28	0.66	0.51			0.40
Cantaloupes			0.24	0.31	0.37	0.61	0.38			0.48
Carrots	0.16	0.18	0.19	0.52	0.64	0.28				0.33
Celery				0.15	0.14	0.25	0.45	0.70	0.85	0.42
Citrus	0.41	0.36	0.44	0.43	0.44	0.41	0.41	0.64	0.41	0.44
Corn				0.12	0.38	0.42	0.26	0.10		0.26
Fruit (deciduous)	0.14	0.45	0.49	0.74	0.71	0.55	0.43	0.36		0.48
Grain sorghums			0.07	0.30	0.39	0.30	0.15			0.24
Grain and Hay	0.50	0.75	0.58	0.12						0.49
Grapes (Muscat)		0.13	0.24	0.26	0.31	0.26	0.26	0.18		0.23
Hops		0.07	0.12	0.31	0.61	0.61	0.38			0.35
Ladino Clover	0.50	0.81	0.55	0.77	0.83	0.76	0.70	0.44		0.67
Onions (early)	0.28	0.45	0.30							0.34
Onions (late)	0.28	0.45	0.30	0.31	0.28					0.32
Pasture	0.11	0.25	0.29	0.33	0.31	0.32	0.32	0.22	0.14	0.25
Peaches	0.22	0.45	0.43	0.46	0.51	0.51	0.38	0.60	0.41	0.44
Peas	0.28	0.36	0.49	0.31						0.36
Potatoes (early)	0.55	0.72	0.73	0.62						0.66
Prunes	0.17	0.34	0.34	0.50	0.48	0.32	0.42	0.48	0.24	0.37
Rice		0.32	1.34	1.42	1.40	1.44	0.51			1.07
Sudan Grass			0.24	0.33	0.37	0.35	0.28	0.24		0.30
Sugar Beets	0.19	0.27	0.55	0.87	0.69	0.36	0.15	0.10	0.03	0.36
Tomatoes				0.32	0.41	0.71	0167	0.81		0.58
Walnuts		0.36	0.43	0.57	0.67	0.63	0.26	0.36	0.24	0.44
Watermelons				0.15	0.18	0.25	0.51			0.27

a/ Based upon consumptive use date for Davis, California, published in "Suggested Subject Matter for Presentation at Irrigation Meetings" by L. J. Booher, 1948, College of Agricultural Extension Service, Davis, California.

TABLE 4-3

CONSUMPTIVE USE COEFFICIENTS - SUGAR CANE AND BANANAS FOR USE IN THE HARGREAVES FORMULA

(Caribbean Area)

CROP	MONTHLY CONSUMPTIVE USE COEFFICIENTS "k"												SEASONAL COEFFICIENT "k"
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Sugar Cane *	0.77	0.69	0.49	0.52	0.53	0.56	0.59	0.73	0.85	0.84	0.91	0.86	0.70
Bananas	0.86	0.85	0.73	0.88	0.85	0.86	0.85	0.78	0.88	0.86	0.76	0.78	0.83

* Planted in March

Where u_1 = measured windspeed in miles per day at height h in feet.

= Slope of saturated vapor pressure curve of air at absolute temperature T_a in ° F. (mm. Hg/° F.)

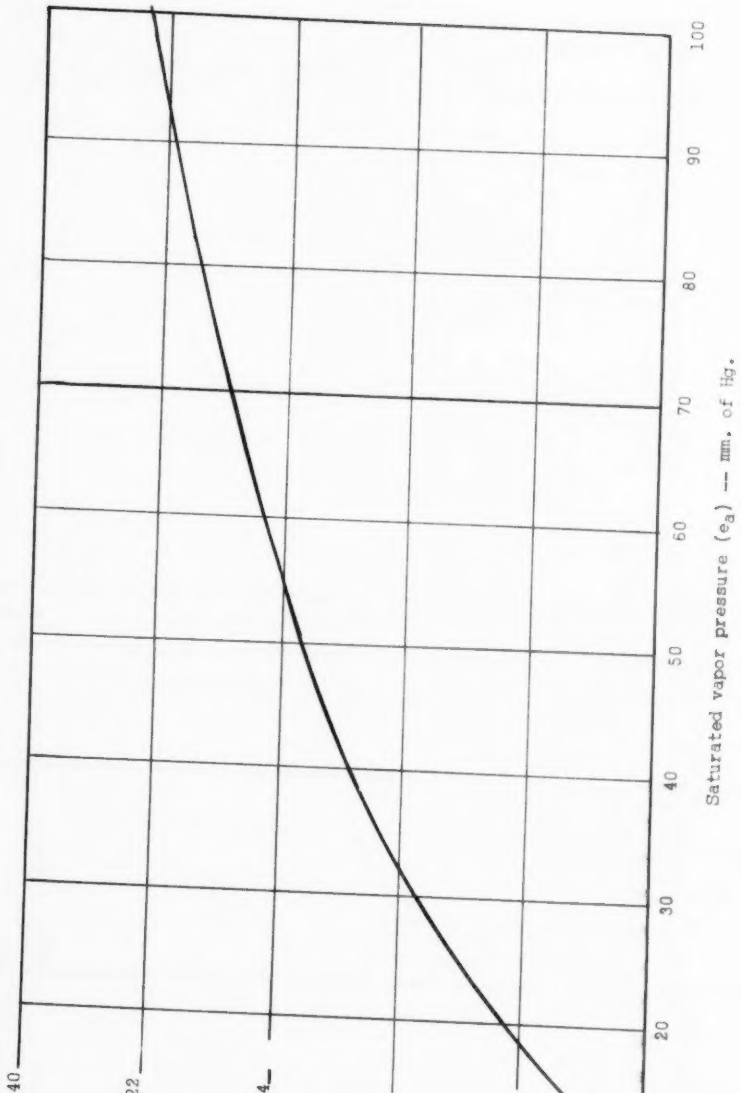
In order that the various factors might be systematically evaluated in the complex formula, the following computation sheet was developed and contains an example on the use of the method. (See Table 5.1):

Table 5.1 Computation sheet for Penman method of computing evapo-transpiration

Location: Boise, Idaho Latitude: 43°34′ Crop: Alfalfa Frost-free period: 4/23-10/17

A.	DATA:	July
	1. Air Temp. -	72.5
	2. Relative humidity - % (Est.)	40
	3. Sunshine n/N - % (Est.)	70
	4. Windspeed, u_2 - Mi/day at 2 m. (Est.)	135
	5. Radiation rate, R_A - mm. H_2O/day (see table 5.2)	16.2
	6. Reflection coefficient - % (Est.)	25
B.	SOLVING EXPRESSION: $R_A(1 - r)(0.18 + 0.55n/N)$	
	7. $(1 - r)$	0.75
	8. $(0.18 + 0.55n/N)$	0.565
	9. Item 6 x item 7 x item 8	6.85
C.	SOLVING EXPRESSION: $\sigma T_a 4(0.56 - 0.092 \sqrt{e_d})(0.10 + 0.90\ n/N)$	
	10. Vapor pressure	
	(a) Saturated, e_a (See fig. 5.1)	21.0
	(b) Actual e_d = (R.H. x e_a)	8.4
	(c) $\sqrt{e_d}$	2.9
	11. $\sigma T_a{}^4$ (See table 5.3)	15.37
	12. $(0.56 - 0.092 \sqrt{e_d})$	0.29
	13. $(0.10 + 0.90\ n/N)$	0.73
	14. Item 11 x item 12 x item 13	3.25
D.	SOLVING FOR H	
	15. Item 9 minus item 14	3.61
E.	SOLVING FOR	
	$E_a = 0.35\ (e_a - e_d)\ (1 + 0.0098\ u_2)$	
	16. $0.35(e_a - e_d)$	4.41
	17. $(1 + 0.0098\ u_2)$	2.32
	18. Item 16 x item 17	10.2
F.	SOLVING FOR $E_T = \dfrac{\Delta H + 0.27\ E_a}{\Delta + 0.27}$	
	19. Δ (see fig. 5.2)	0.65
	20. ΔH	2.23
	21. $0.27\ E_a$	2.75
	22. $\Delta + 0.27$	0.92
	23. E_T = (mm. of water per day)	6.67
	(in. of water per day)	0.26
	(in. of water per month)	7.18

Figure 5.1. TEMPERATURE VS. SATURATED VAPOR PRESSURE



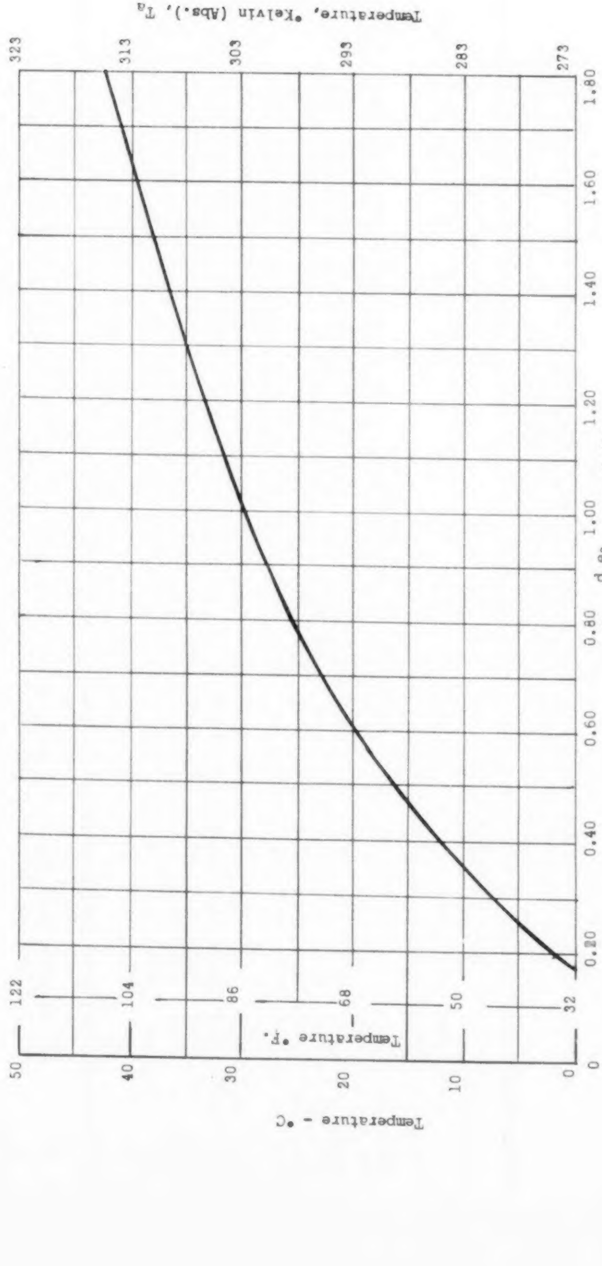


Figure 5.2. Temperature vs $\Delta\left(\frac{\text{d Saturation Vapor Pressure, m.m. Hg}}{\text{d Temperature, °F}}\right)$ for use with Penman's method for calculating evapo-transpiration

Table 5.2. Mid monthly intensity of solar radiation (R_A) on a horizontal surface in m.m. of water evaporated per day. 1/

	Northern Hemisphere										Southern Hemisphere								
	90°	80°	70°	60°	50°	40°	30°	20°	10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
Jan.	--	--	--	1.3	3.6	6.0	8.5	10.8	12.8	14.5	15.8	16.8	17.3	17.3	17.1	16.6	16.5	17.3	17.6
Feb.	--	--	1.1	3.5	5.9	8.3	10.5	12.3	13.9	15.0	15.7	16.0	15.8	15.2	14.1	12.7	11.2	10.5	10.7
Mar.	--	1.8	4.3	6.8	9.1	11.0	12.7	13.9	14.8	15.2	15.1	14.6	13.6	12.2	10.5	8.4	6.1	3.6	1.9
Apr.	7.9	7.8	9.1	11.1	12.7	13.9	14.8	15.2	15.2	14.7	13.8	12.5	10.8	8.8	6.6	4.3	1.9	--	--
May	14.9	14.6	13.6	14.6	15.4	15.9	16.0	15.7	15.0	13.9	12.4	10.7	8.7	6.4	4.1	1.9	0.1	--	--
June	18.1	17.8	17.0	16.5	16.7	16.7	16.5	15.8	14.8	13.4	11.6	9.6	7.4	5.1	2.8	0.8	--	--	--
July	16.8	16.5	15.8	15.7	16.1	16.3	16.2	15.7	14.8	13.5	11.9	10.0	7.8	5.6	3.3	1.2	--	--	--
Aug.	11.2	10.6	11.4	12.7	13.9	14.8	15.3	15.3	15.0	14.2	13.0	11.5	9.6	7.5	5.2	2.9	0.8	--	--
Sept.	2.6	4.0	6.8	8.5	10.5	12.2	13.5	14.4	14.9	14.9	14.4	13.5	12.1	10.5	8.5	6.2	3.8	1.3	--
Oct.	--	0.2	2.4	4.7	7.1	9.3	11.3	12.9	14.1	15.0	15.3	15.3	14.8	13.8	12.5	10.7	8.8	7.1	7.0
Nov.	--	--	0.1	1.9	4.3	6.7	9.1	11.2	13.1	14.6	15.7	16.4	16.7	16.5	16.0	15.2	14.5	15.0	15.3
Dec.	--	--	--	0.9	3.0	5.5	7.9	10.3	12.4	14.3	15.8	16.9	17.6	17.8	17.8	17.5	18.1	18.9	19.3

1/ Computed from "Manual of Meteorology" by Napier Shaw, Vol. II, Comparative Meteorology, 2nd Edition, Cambridge University Press, 1936, pp. 4 and 5.

Note: Values from the table by Shaw multiplied by 0.86 and divided by 59 gives the radiation in mm. of water per day.

Table 5.3 Values of σT_a^4 for various temperatures when computing evapotranspiration by the Penman method.

Temperature	σT_a^4	Temperature	σT_a^4
° Abs.	mm H_2O/ day	°F.	mm H_2O/day
270	10.73	35	11.48
275	11.51	40	11.96
280	12.40	45	12.45
285	13.20	50	12.94
290	14.26	55	13.45
295	15.30	60	13.96
300	16.34	65	14.52
305	17.46	70	15.10
310	18.60	75	15.65
315	19.85	80	16.25
320	21.15	85	16.85
325	22.50	90	17.46
		95	18.10
		100	18.80

Note: Heat of vaporization was assumed to be constant at 590 gal./gm of H_2O.

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CONTENTS

DISCUSSION
(Proc. Paper 1521)

EVAPORATION FROM FREE WATER SURFACES AT HIGH ALTITUDES[a]

Closure by Harry F. Blaney

HARRY F. BLANEY,[1] M. ASCE.—The discussors of this paper have brought out some facts which add to the limited literature of the subject. The pioneering research by Mr. Rohwer, M. ASCE, will always be recognized in any evaporation studies.(3) The author agrees with Mr. Rohwer's conclusion that other factors influencing evaporation are usually more important than altitude. More attention should be given to factors such as wind velocity, water temperature and vapor pressure in estimating evaporation if these data are available. The computed annual evaporation, 32.90 inches, at Fort Collins by Mr. Rohwer (shown in table) based on the Colorado Land pan record is remarkably close to the 33.96 inches computed by the author in table 7. This close agreement indicates that the formula $e = kf$ = monthly evaporation gives reasonable results. The author has found that corrections for wind movement are minor when the average velocity does not exceed 3 miles per hour. Evaporation from the Weather Bureau type of pan and air temperatures are influenced by relative humidity and they apparently counterbalance the humidity factor in the formula in semi-arid climates.

The discussion by Mr. Kenneth M. Turner has employed the monthly use factor $f = \frac{t \times p}{100}$ in the author's formula to a good advantage in table 1 (table 9) and figures 1 and 2 (figures 5 and 6). However, the item "monthly use factor" shown in table 1 (table 9) should be changed to "Sum of monthly use factors for the year" as the values given are annual rather than monthly use factors. The "pan factor" of 0.80 for the Weather Bureau pan appears high for arid climate. A factor of 0.70 is usually used. A study made by the author at Silver Lake, California, indicates that a factor of 0.60 should be used in converting evaporation from a Weather Bureau pan to reservoir evaporation in arid climates.(14) Mr. Turner indicates that humidity is the only variable which explains the confusion between the semi-humid and arid evaporation records shown in table 1. The annual wind movement varies from 10,420 miles at Lake Tahoe to 23,930 miles at Falton. It is undoubtedly a factor that should be considered in computing reservoir evaporation. The author has found that evaporation from a Weather Bureau pan and temperature records automatically takes care of some of the differences in humidity. Figure 2 shows a good correlation of monthly use factor (f) and pan evaporation at Lake Tahoe and Falton. The author, when preparing the

a. Proc. Paper 1104, November, 1956, by Harry F. Blaney.

1. Prin. Irrig. Engr., Western Soil and Water Management Section, Soil and Water Conservation Research Branch, Agri, Research Service, U. S. Dept. of Agriculture, Los Angeles, Calif.

paper, found a similar relationship for Huntington Lake. Mr. Turner points out that the formula $e = k\frac{t \times p}{100}$ can be used to estimate evaporation for months of missing pan records. The method has been employed by the author many times when some monthly records are missing and annual evaporation is needed. The author does not agree with Mr. Turner's statement "that any empirical evaporation formula would have to include humidity and air movement as parameters as well as temperature" when applied to semi-arid climates. The discussion by Mr. Rohwer checks the author's computation of annual evaporation at Fort Collins with a difference of only 1.06 inches. The author has found that the ratio between evaporation and temperature at one station can be used to estimate annual evaporation for another station having similar climate. The San Francisco Bay investigation(15) had demonstrated that the formula $u = kf$ can be used to estimate evaporation fairly accurately. Several good formulae have been developed(3,6) to include wind movement, humidity and water temperature as well as air temperature. Average published humidity and water temperatures usually are not available for areas where an estimate of evaporation is needed.

Messrs. Irvin M. Ingerson and John W. Shannon have called attention to a fact known by research engineers that the size and shape of water surface areas influence the amount of evaporation. Studies made of evaporation from pans located at six different sites at the Morris Reservoir in Los Angeles County in 1939, indicate a variation of 30 percent at this irregular shaped mountain reservoir. A study by the author of evaporation at three stations adjacent to Salton Sea, California(16) shows a variation in pan evaporation of about 25 percent, depending upon whether the prevailing wind was moving dry air over the pans from the desert land or from moist air which had passed over Salton Sea.

Another method of estimating monthly winter evaporation at high altitudes has been employed by the author. The procedure is to plot monthly evaporation the entire year at a nearby lower elevation station against available monthly measurements during the frost-free period at the high elevation station. For example, a straight line was fitted to the plotted points from observations at Huntington Lake (elevation 6954 ft.) and Friant Station (elevation 400 ft.) shown in figure 7. An equation, ($e_H = 0.486\ e_F + 0.41$ = monthly Weather Bureau pan evaporation), was developed for computing the evaporation for the winter months at Huntington Lake.

The author acknowledges the assistance rendered by Gilbert L. Corey, formerly irrigation engineer of the Western Soil and Water Management Section, ARS, USDA, in the compilation of data for this paper.

LITERATURE CITED

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15. Evaporation and Evapotranspiration Investigations in the San Francisco Bay Area. By Harry F. Blaney. Vol. 36, No. 5 Trans. Amer. Geo. Union Oct. 1955.

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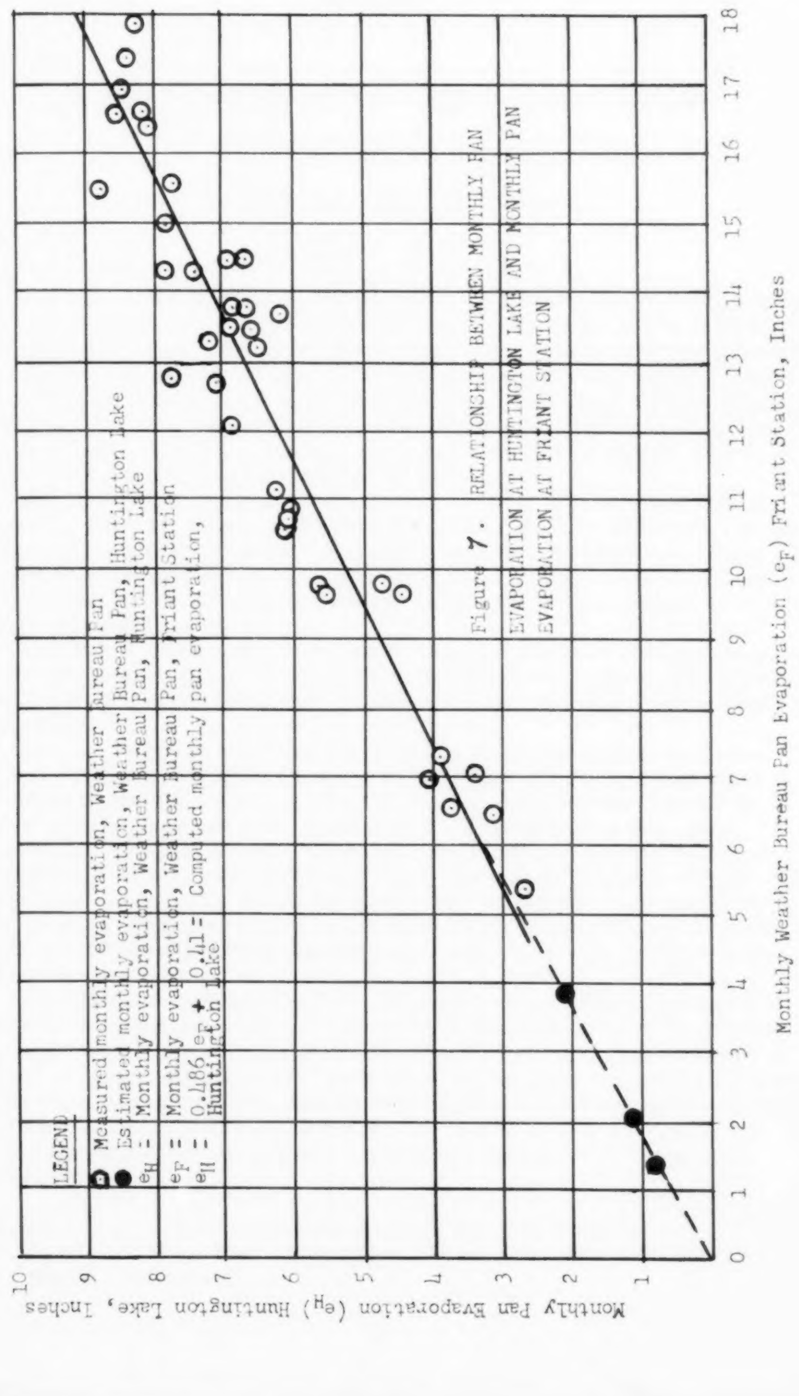

Figure 7. RELATIONSHIP BETWEEN MONTHLY PAN EVAPORATION AT HUNTINGTON LAKE AND MONTHLY PAN EVAPORATION AT FRIANT STATION

IRRIGATION REQUIREMENTS BASED ON CLIMATIC DATA[a]

Closure by George H. Hargreaves

GEORGE H. HARGREAVES,[1] A.M. ASCE.—The discussion of this paper by Mr. Selim presents a comparison of consumptive use computed by the Blaney-Criddle formula and field deliveries during the dry season in Egypt. The data presented indicate that the Blaney-Criddle method gives satisfactory results in the computation of seasonal consumptive use. The Blaney-Criddle formula was developed and used principally in the arid and semi-arid portions of the United States. Coefficients from these areas should apply equally well to the other arid and semi-arid portions of the world.

The Blaney-Criddle method has also been used to give seasonal requirements in other climatic classifications by making suitable adjustments in the consumptive-use coefficients. This paper, however, develops a method of estimating monthly values of consumptive use as a basis of design and for scheduling irrigation. Consumptive use is obtained from measured or calculated values of evaporation.

Recently Equation 4 has been used to compare computed values of evaporation with measured evaporation at Ambuklao in the Philippines. The results were not as satisfactory as anticipated. Additional refinement of the equation is needed.

Several studies demonstrate the value of evaporation data in computing consumptive use (Equation 5). Penman(1) working with short grass cover in England found values for k of 0.6 for November through February; 0.7 for March, April, September and October; and 0.8 for May through August. Pruitt and Jensen(2) working at Prosser, Washington with sugar beets and potatoes correlated measured consumptive use with evaporation and with consumptive use computed by the Blaney-Criddle and Thornthwaite methods. A correlation coefficient of 0.84 was determined for evaporation as compared with a coefficient of 0.78 for the Blaney-Criddle method and of 0.76 for the Thornthwaite method.

Long periods of evaporation records using white and black Livingston spherical porous porcelain atmometers have been kept at Davis, California, together with measurements of the use of water by crops. In an analysis of these records Halkias, et al.(3) correlated difference in evaporation for black and white atmometers with monthly consumptive use of water by ten different crops and found coefficients of correlation of 0.95 to 0.99, averaging 0.98. An equation for the relationship is presented in a form similar to that of Equation 5.

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a. Proc. Paper 1105, November, 1956, by George H. Hargreaves.

1. Water Resources Engr., International Cooperation Administration (ICA), Manila, Philippines.

Consumptive use of water by crops under identical climate conditions is found to be the same if ground coverage is equivalent. Tall trees use the same amount of water as a low growing crop such as alfalfa if the ground is covered to the same extent with each crop.

Further analysis of the data presented by Halkias, et al. indicate a high degree of correlation between U. S. Weather Bureau pan evaporation and consumptive use. The equation developed by the method of least squares is

$$u = k\,(e + 2.70) \tag{6}$$

where u is the monthly consumptive use of water by the crop; k is a monthly consumptive use coefficient, depending primarily upon the extent of ground coverage by the crop, and e is evaporation in inches.

The relationship between irrigation requirements and climate has been developed in some detail at Davis. It is, however, difficult to apply this relationship to humid or tropical conditions. Effects of cloudiness and high humidity upon consumptive use require further analysis. In order to accomplish this, the Hydrographic Section, Irrigation Division, Bureau of Public Works, has established 13 evaporation stations in the Philippines. These are presently equipped with evaporation pans, Piche evaporimeters and instruments for measuring temperature, humidity and wind movement. Black and white atmometers will be installed in each station. Data are to be analyzed in order to evaluate the influence of climate on evaporation and to assist in determining irrigation requirements as a basis for design and for scheduling irrigation deliveries.

Note: On page 1105-4, at the end of the last line, the words "coefficient; and e is the monthly consumptive use." should be added.

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2. Pruitt, W. O. and Jensen, M. C., Determining when to Irrigate, Agricultural Engineering, June 1955.

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PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Board of Direction are identified by the symbols (BD). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper numbers are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 1449 is identified as 1449 (HY 6) which indicates that the paper is contained in the sixth issue of the Journal of the Hydraulics Division during 1957.

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c. Discussion of several papers, grouped by Divisions.